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NuMI Hadronic Hose
Technical Design Report

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Abstract

The Hadronic Hose is a magnetic focusing device which would be installed in the decay pipe of the NuMI neutrino beam line. The primary motivation is to reduce the differences in the shape of the neutrino spectra at the MINOS far and near detectors. The reduction in near/far differences will reduce the systematic uncertainties in neutrino oscillation measurements.

The beam focusing element of the Hadronic Hose is 644 m of wire running down the center of the decay pipe. A current pulse of 1000 Amps in the wire produces a toroidal magnetic field. The current is returned through the steel decay pipe. In this field, pions orbit with trajectories that sweep their neutrino decay fluxes across the centers of the near and far detector which helps to average out near and far differences.

Other benefits of the Hadronic Hose are to increase the neutrino flux and to modestly loosen focusing horn tolerances.

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1 Introduction

The Hadronic Hose is a magnetic focusing device which would be installed in the decay pipe of the NuMI neutrino beam line. The primary motivation is to reduce the differences in the shape of the neutrino spectra at the MINOS far and near detectors. The reduction in near/far differences will reduce the systematic uncertainties in neutrino oscillation measurements. Other benefits of the Hadronic Hose are to increase the neutrino flux and to modestly loosen focusing horn tolerances.

The physics case for the Hadronic Hose is laid out in "Proposal to Include Hadronic Hose in the NuMI Beam Line" [1], and will not be repeated here. This document describes the technical design details necessary to implement the Hadronic Hose.

Hadronic Hose Hardware overview

The beam focusing element of the Hadronic Hose is 644 m of wire running down the center of the decay pipe. A current pulse of 1000 Amps in the wire produces a toroidal magnetic field. The current is returned through the steel decay pipe. In this field, pions orbit with trajectories that sweep their neutrino decay fluxes across the centers of the near and far detector which helps to average out near and far differences.

The hadronic hose hardware consists of:

- The current-carrying wire in the center of the decay pipe, which is divided into 72 sections each 30 feet long.
- Support spiders to keep the current-carrying wire centered in the decay pipe. Three 1-meter long 20 mil diameter invar wire loops connect the wire to the support mounting brackets, which have tooling ball holes for precision survey, adjustment for hose alignment, and ceramic for electrical insulation. Nine spiders are used per 30 foot long hose segment.
- Wire tension supports, with 20 mil invar wire and a turning bracket for connecting to the current carrying wire, and a mounting bracket with constant tension spring and ceramic insulator to connect to the decay pipe wall. Four spring brackets are used per 30 foot hose segment.
- Ground strap with good electrical contact to inside of decay pipe, since decay pipe is used as the electrical return path.
- Vacuum electrical feedthrough, two per segment.
- Capacitor bank which provides a 4.5 kV, 4000 Amp, 300 μsecond pulse to the power distribution stripline once every 1.87 seconds.

- Aluminum stripline to carry power down decay pipe passage-way.
- Transformer for each segment, which converts the stripline power to a 250 Volt, 1000 Amp pulse.
- Charging supply for capacitor bank, and core bias supply for the transformers.
- Transformers and readout to monitor current in the hose segments, including cable tray to hold monitoring cables.
- RAW water system with tubes running along the decay pipe to keep the decay pipe cool.

Design parameters are listed in Table 1.

Changes since proposal

Since the time of the proposal, the NuMI proton extraction scheme has been changed from resonant extraction to single turn extraction, which reduces the beam spill from 1 msec to 10 μsec. This allows reduction of the hose pulse length, leading to a substantial reduction in heating of the hadronic hose wire, as well as reducing the capacitor bank necessary in the power supply.

After some study of the heat flow in the decay pipe, a system for water cooling the pipe has been added. This cooling reduces expansion and stess in the pipe/concrete-shield system, thus reducing the risk of loss of alignment by decay pipe movement, and also lowers the hose wire temperature.

Hose support hardware installation is about 18 months away, and actual installation of the hose wire is at least 30 months away. The design of the support hardware has thus been the priority. A year of testing of different wire materials is envisioned, before the final choice of wire is made. The baseline design shown will be for Al 1350, but current information on two other choices is also presented.

A beam plug which reduces the high energy neutrino rate may be desirable for the NuMI Low Energy Beam. This would substantailly reduce the direct beam heating of the hose wire. (The plug increases the heating of the decay pipe wall in some locations, which partially offsets the temperature reduction of the hose wire).

Monte Carlo simulation indicates that the first couple meters of the hadronic hose experiences by far the worst beam heating. The current hose design adds a 2 m section of unpulsed wire at the beginning, which lowers the maximum beam heating of the pulsed section by a factor of 10. Since this wire does not carry current, it can be made of a stronger Aluminum alloy with lower electrical conductivity, or even be made of Beryllium. This 'beam shield' allows the hardware design of the hose to be essentially independent of whether or not there is a beam plug.

2 Hadronic Hose Design Parameter List

Parameter	Baseline
Radius, thickness of decay pipe	1 m, 12.7 mm
Wire material	Aluminum 1350 H18
Wire radius	1.19 mm
Number of segments	72
Length of segment	8.94 m
Gap between segments	0.2 m
Expansion of a segment 20°C to 87°C	0.015 m
Start distance from 1st horn	50 m
Unpulsed beam shield section length	2 m
Distance between wire supports	1.111 m
Peak Current	1000 Amps
Half sine-wave baseline	300 μsec
Wire resistive voltage drop per segment	86 Volt
Maximum voltage drop per segment	215 Volt
Inductance per segment	13 μhenry
Vacuum	0.1 torr
Temperature jump from i^2r heating	0.10° C
Temp. jump from beam heating	0.21° C
Emissivity of anodized wire	0.5
Heat trans. coef. residual gas	3.0 w/m^2/K
Wire temperature	86° C
Decay pipe temperature	55° C
Wire segment expansion per pulse	0.07 mm
Tension on wire	2 lbs
Stress from pretension	290 psi
Sag of wire	2 mm
Alignment tolerance	2 mm

Table 1: Baseline Hose design parameters.

3 Wire

The hose wire should be kept to less than 1.4 mm radius so that the absorption of pions orbiting the wire does not become a significant systematic error.

The hose wire is made in sections for several reasons: to keep the voltage on each section below breakdown, to allow wire expansion/creep to be taken up periodically down the wire rather than all at the end of the decay pipe, and to allow the rest of the hose to operate in case of a local failure. On the other hand, the longer each segment the cheaper the hose is, and the less extraneous material is in the beam.

The hose test cell experienced no sparking with less than 375 volts at any pressure [1], and the minimum sparking potential in Air is 327 V [2]. A hose design goal of less than 250 volts is chosen. At 1000 Amps, this would imply that a hose section could have a maximum resistance of 0.25 Ohm. However, because of significant inductance in the decay pipe (1.4 μhenry/m), the resistance should be kept to about half that.

For Aluminum wire less than 1.4 mm radius, the above limits the length of a section to order 10 m. We presuppose that the civil construction of the decay pipe may be made in 10' sections, so we fix the length of a section to 30'. This can be varied to some extent to match whatever the civil construction actually wants for section length.

Table 2 lists operating points for three wire material selections.

(A thermal expansion coefficient of $24 \times 10{-}6\ \mathrm{K}^{-1}$ is shown in the table for Aluminum. During testing, with a thick 3 mil anodization layer on 31 mil radius wire, the expansion coefficent for aluminum wire was reduced to $18 \times 10{-}6\ \mathrm{K}^{-1}$, but this effect should be nearly negligible for the baseline design of 0.4 mil to 1 mil anodizing on 47 mil radius aluminum wire).

For Aluminum wire, a 3/32 inch diameter (1.19 mm radius) is selected as a compromise between minimizing pion absorption and keeping joule heating and voltage low. For Copper, the wire diameter was reduced as much as possible consistent with the voltage/section limitation, in order to minimize the beam heating.

3.1 Wire Cooling

The residual gas in the decay pipe can contribute significantly to the cooling of the wire. In tests done with the hadronic hose test stand with 0.079 mm radius wire, the rate of convective cooling at atmospheric pressure was about 50% higher than one might expect from a comparison to tables of heat loss developed for steam pipes, and followed the expected trend that higher temperatures,

Wire Material	AL 1350	AL 6201	Cu C10100
Density (g/cm^{-3})	2.70	2.69	8.94
Resistivity at 20°C (μohm cm)	2.70	3.22	1.71
Resist. slope (μohm cm/°C)	0.010	0.0125	0.0068
Wire radius	1.19 mm	1.19 mm	0.814 mm
Beam energy dep. (GeV/g/POT)	3×10^{-5}	3×10^{-5}	9×10^{-5}
ΔT/pulse electrical	0.10	0.13	0.28
ΔT/pulse beam heating	0.21	0.21	1.46
Wire cooling coeff. (W/cm-K)	2.2×10^{-4}	2.2×10^{-4}	2.1×10^{-4}
Effective heat trans. coeff. (W/cm^2-K)	3.0×10^{-4}	3.0×10^{-4}	4.1×10^{-4}
Thermal expansion coeff. (K−1)	$24 \times 10{-}6$	$24 \times 10{-}6$	$17.3 \times 10{-}6$
Thermal heat capacity (J/gK)	0.900	0.895	0.385
Thermal expansion over 8.94 m	1.4 cm	1.5 cm	2.4 cm
Resistive voltage 11.33 m 1st segment	86 V	104 V	148 V
Resistive voltage 11.33 m last segment	80 V	97 V	111 V
Voltage w/o gas cooling	90 V	110 V	164 V
Fraction of cooling by gas	39%	39%	38%
Wire Temp. 1st seg.	87°C	89°C	174°C
Wire Temp. last seg.	66°C	68°C	73°C
Temp. w/o gas cooling	104°C	107°C	218°C

Table 2: Operating temperatures for various wire material selections, including cooling from residual gas at 0.1 torr. Unless otherwise indicated, values are for 1st segment, which gets most severe beam heating. Note Copper results above were from a toy MARS run; copper in a full MARS NuMI beam simulation shows somewhat less heating but the operating point has not yet been recalculated.

causing faster convective air current, yielded higher heat transfer coefficients. As the pressure was lowered, the heat transfer coefficent dropped until at 0.1 torr it reached the calculated heat transfer coefficient for conduction through air without convection. Most of the temperature dependence was also gone, as one might expect with conduction rather than convection. This is the range where the mean free path of the gas is comparable to the wire radius. The change in heat transfer coefficient from 760 torr to 0.1 torr was about a factor of three. Thus we use a heat conduction formula to extrapolate to other radii and temperatures:

$$\Delta T = -\frac{P}{L}\frac{ln(b/a)}{2\pi k}$$

where $\frac{P}{L}$ is the power per unit length generated in the wire, b and a are the radii of the pipe and the wire, and k is the thermal conductivity of air, 0.0239 w/mC.

For the baseline described, the gas cooling carries away about 40% of the heat from the wire. At vacuum levels much below 0.1 torr, the gas cooling starts to decrease rapidly.

The aluminum wire is anodized to increase emissivity, and thus improve wire cooling. With a 0.4 mil anodization layer, the emissivity of the aluminum wire measured with the test stand was 0.5, without much dependence on temperature. From an engineering handbook, we had expected an emissivity closer to 0.8.

Copper is quoted as having an emissivity of 0.15 if polished, and 0.6 with an oxide layer, with the emissivity being essentially flat over the temperature region of interest.

3.2 Wire Creep

Tests are underway to measure creep rates of wire in hadronic hose environmental conditions. Wires are also tested in more stressful conditions to aid in extrapolating performance. Data have been taken from three test setups for aluminum wire:

- A specially constructed test stand at Univ. Texas, Austin, with data from 13 wires over one month.
- A commercial creep tester at ANL, with data from 3 wires each tested for one week.
- The Hadronic Hose test stand in at FNAL, with one wire tested for two months.

UTA Tests. Thirteen different wires were placed under different conditions of stress and temperature. Two different alloys, Al1350 and Al6201, were tested. Since the available 6201 sample was 3/16" diameter rather than 3/32", larger weights were attached to achieve comperable stresses. Two of the wires were run at room temperature as a control.

The wires were suspended inside of 2" diameter aluminum tubes and to one end of each wire a brass weight was attached. Each tube was wrapped in heating tape and the ends capped off with high-temperature plastic and operated at elevated temperature for three weeks. The temperature uniformity within the tube was measured with three thermocouples within each tube. It was better than 10°F when there were no wires in the tubes, but variations of $>$ 20°F were experienced when the wires were strung (the wires protruding out the bottoms of the tubes with their brass weights attached acted as heat antennas).

The positions of the wires' ends as they stretched was measured by placing the whole assembly over a granite reference table and using a set of conventional gauge blocks and dial indicators to measure the height of the brass weight above the reference table. The repeatability of these measurements was ∼0.001".

During the first 200 hours of operation at elevated temperature, the wires all stretched by several mm, presumably due to straightening of the wires aided by heat (note that the control samples did not demonstrate this elongation). The rate of stretching is in general gradually slowing down. The creep rates labeled A-F in Figure 1 are the slopes of the wires' elongations as measured during the last 77 hours out of 600 hours total operation. Interestingly, many of the wires 'untwisted' during the testing, indicating that some material stresses were annealed out of the wires. This untwisting is still evident in some of the wires, indicating that not all the straightening or annealing is complete. (Note the AL 6201 samples were obtained by unraveling strands from heavy duty power cable).

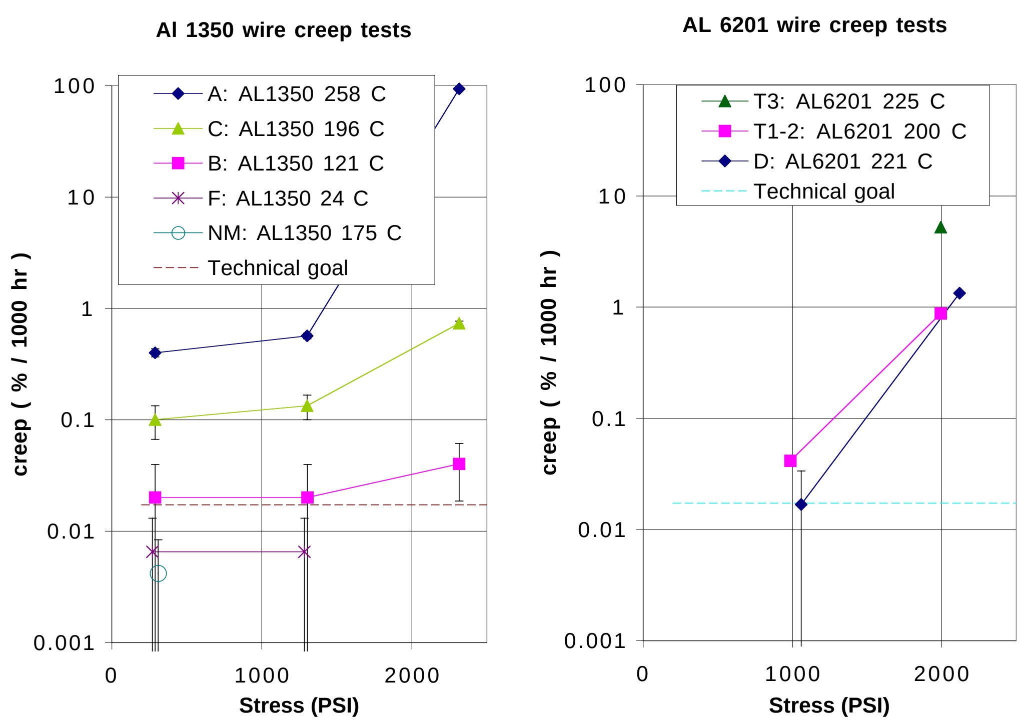

Figure 1: Creep data measurements taken as part of hadronic hose R&D. In order to put points with zero measuremed creep on a log plot, zero creep points are plotted at half the measurement least count.

ANL Tests [3]. Long term creep for many aluminum alloys follows the formula:

$$\dot{\epsilon} = A\sigma^{4.4}e^{-Q/RT}$$

where $\dot{\epsilon}$ is the steady-state strain rate, σ is the applied stress, R is the gas constant, T is absolute temperature, and Q is the activation energy for creep. For aluminum, Q/R = 17087 K. The data labeled T1-3 in Figure 1 were taken at elevated stress and temperature to check this dependence for AL 6201 and to derive the constant A. Both the temperature dependence and stress dependence are found to be consistent with the formula. This is the most controlled of the hose wire tests done, with oven temperature consistent and controlled over the wire length better than 1°C and strain measurements better than 0.1 mil.

FNAL Test Stand. Here the AL 1350 wire was in an evacuated tube, maintained under tension with a spring, and heated by passing an electric current through it. The measurement accuracy is 5 mil over 141 inches, the temperature is estimated from the thermal expansion of the wire to a few °C. The data point labeled NM in Figure 1 is the average over the second of two months of operation with the wire.

AL 1350. The line in Figure 1 labeled Technical Goal is derived by requiring that the end of a section creep by no more than 4 cm over eight years of running nine months per year. The creep will be taken up by the constant tension spring mounting and deflection of the spider supports.

The creep rates shown in Figure 1 for AL 1350 are just barely acceptable for the needs of the Hadron Hose, but further study is necessary to resolve whether the elongations observed at low stress are truly creep or are still from the wire straightening out and an initial faster creep phase. (The FNAL measurement, being the lowest and taken after the longest time is certainly consistent with the creep rate continuing to decrease; also the extrapolation from higher stress and temperature using the formula for creep is for a much smaller rate).

It is evident that study of how to straighten the wires prior to installation into the NuMI decay pipe is critical. Both reduction of primary creep and straightening of the wire may be accomplished by pre-creeping the wire before installation at temperatures similar to those expected during actual running and slightly higher stress.

AL 6201. As shown in Figure 1, AL 6201 appears very promising. The fact that the UTA creep rates (labeled D), taken at the end of a month, are lower than the ANL rates (labeled T) indicate that the ANL samples may still have been suffering some primary creep. Using the ANL points and creep formula to extrapolate, the creep rate at 1000 psi and 160°C would be acceptable, while our design operating condition is a much less severe 290 PSI and 89°C. Samples run for longer times, and at lower temperatures and stress, are definitely needed; we have now received AL 6201 wire which is of the proper diameter, and which is not initially twisted as the previous samples were.

Copper Wire. While NuMI has not done any tests with copper, Figure 2 shows that copper wire at 1000 PSI and 205 C has an acceptable creep rate of 4×10^{-6} %/hr. This is 1.9 cm per segment over 8 years of running 9 months per year, and can be taken up by the spring loading of the segment wires.

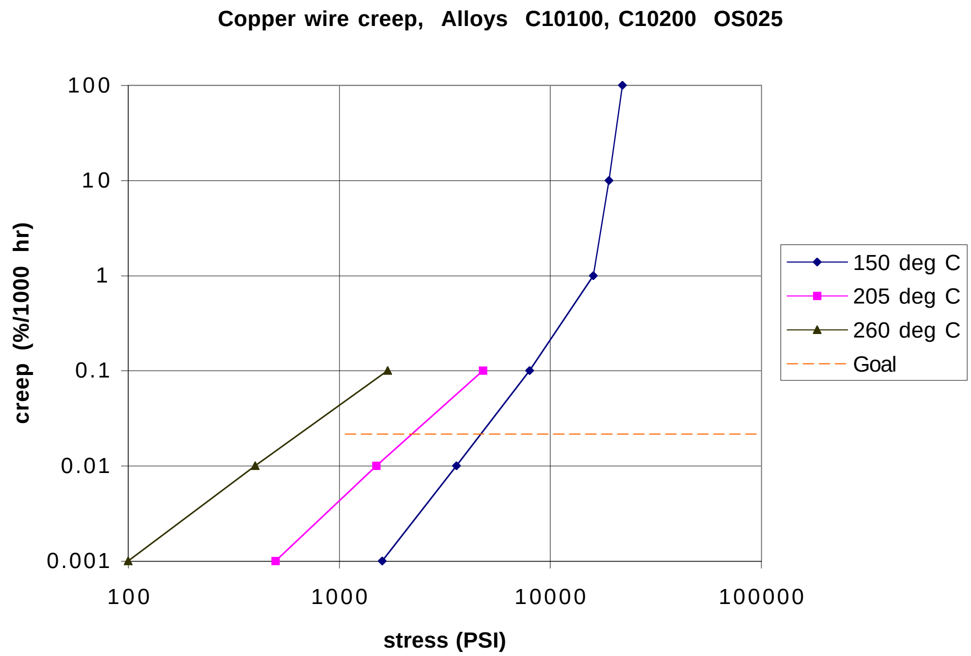

Figure 2: Creep data for copper. (Data taken from Metals Handbook [4].

Along with longer term tests of aluminum wire at lower stress and temperature, tests with Copper wire are planned.

3.3 Wire Sag versus Tension

Reduction of tension reduces creep rate, but to maintain alignment the wire must then be supported more often. In order to be able to stand up between support spiders during installation, a minumum of about 1 m spacing is needed, and we have selected 43.75" spacing to evenly match 29'4" long segments with 9 support spiders and leave 8" for turning brackets and wire expansion/creep.

Treating the wire as a limp string with the density of aluminum, the sag δ in mm due to gravity is given by $\delta = 480L^2/\sigma$ where L is the distance between supports in m and σ is the wire tension per unit area in PSI. (The wire initially is far from being a limp string, but at elevated temperatures over long times can relax like one). This gives $\delta = 2.06$ mm for L = 1.12 m and $\sigma = 290$ PSI, which corresponds to 2 lbs tension on a 3/32" diameter wire.

Because of its higher density, a copper wire requires 3.3 times the tension per unit area to achieve the same sag.

4 Unpulsed Section

A one-quarter length hose section is installed as the first section in the decay pipe but is not pulsed (Figure 3). Its purpose is to take the brunt of the beam heating, and protect the rest of the hose. This reduces the beam heating in the first pulsed section of the hose by an order of magnitude. Bringing out its electrical connections like a regular section allows an electrical continuity check to be made to see if it is broken. It can also function as a charge-read-out (Budal style) monitor of the beam, similar to the NuMI target monitor.

5 Wire Supports and Feedthroughs

Figure 4 shows the location of hadronic hose hardware in relation to the decay pipe, shielding, and decay pipe passage-way.

The scheme which applies spring tension on the current carrying wire inside the decay pipe is shown in Figure 5. Note that no electrical connections or crimp joints are attempted at the center of the decay pipe, since that is where beam heating of the wire makes it hottest, but that connections are made at the outer radius. Support spiders without springs are then used to keep the wire centered. Tension is maintained on the hose wire with constant tension springs. Thus the tension does not vary as the wire expands or creeps.

As shown in Figure 6, the vacuum feedthrough is at the decay pipe wall. The box beam from the decay pipe wall out to the decay pipe passage-way serves only to protect the wire during the concrete pour or if the concrete cracks, and can be filled with poly beads to reduce radiation leakage to the passageway.

Both the feedthrough and spring bracket are welded to the decay pipe wall. The Aluminum wire is silvered on the end, where it will be brazed to the copper.

Figure 7 shows a groundstrap tack welded around the inside of the decay pipe, and connected to the feedthroughs.

Each section has a central current-carrying hose wire plus spider support wires to keep the hose wire centered and spring tension wires to keep the hose wire pulled taught. Figure 8 shows how alternating hose sections have their lead

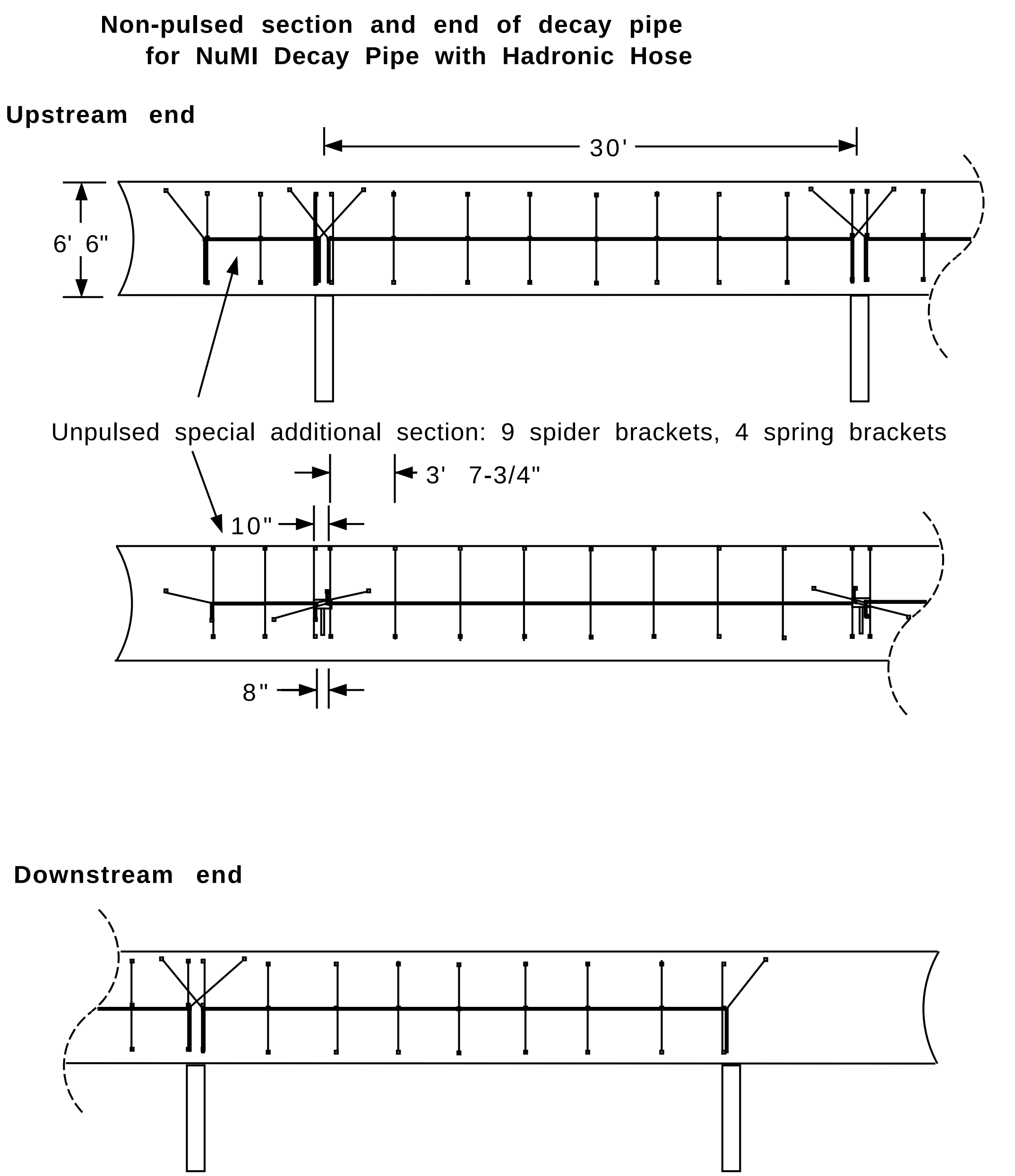

Figure 3: Hose wire in decay pipe, showing extra unpulsed short section on upstream end.

wire tilted up or down at 15°, so that the balancing tension support wires do not interfere with each other or with the spider support wires.

Figure 9 shows details of the spider alignment bracket, which is welded to the decay pipe and has a hole for a precision alignment tooling ball.

Figure 10 details all spider bracket weld locations, and relation to box beams and holes drilled in the decay pipe for feedthroughs.

Figure 11 similarly details all spring tension bracket weld locations. Because of the alternate 15° up and down orientation of the hose wire leads, these brackets also alternate orientation.

Figure 12 shows the anodized 6061-T6 aluminum bracket which transmits the tension to the hose wire in the center of the decay pipe. The current carrying hose wire follows the gentle turning radius, while the tension is balanced by a 20 mil diameter invar wire threaded through the small hole at the center of the turn. The flat thin membrane gives strength and supplies a large surface to volume ratio for radiating heat. Large holes are to reduce mass. Since half of the wire surface is closed off to radiative and air cooling by the braket, the bracket must take up some of the wire cooling load. If necessary, an Indium foil between the bracket and wire could be used to improve the heat conduction.

Not shown yet is a penetration from the horn power supply room to the target hall, similar to the horn stripline penetration.

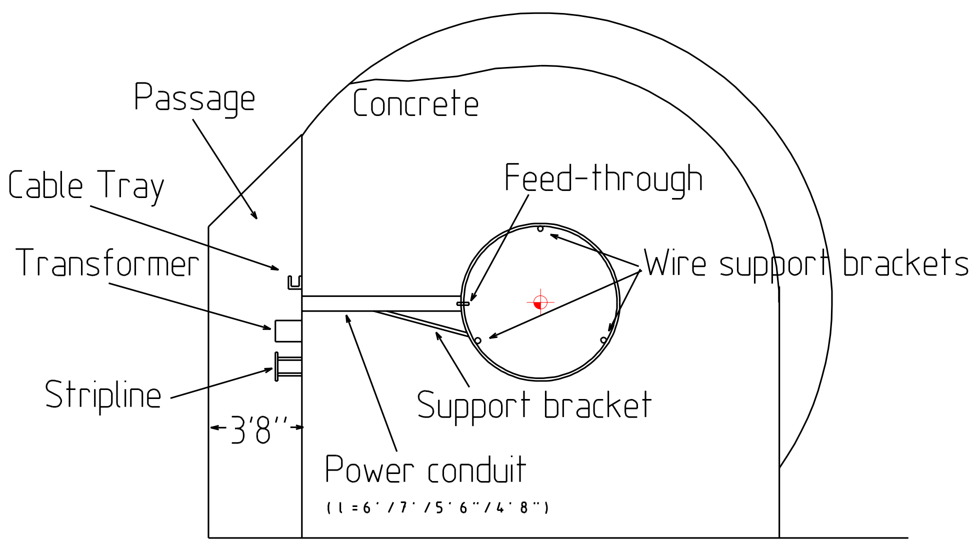

Figure 4: Hadronic hose, stripline, transformer, and monitor cable cable-tray in decay pipe and passage-way.

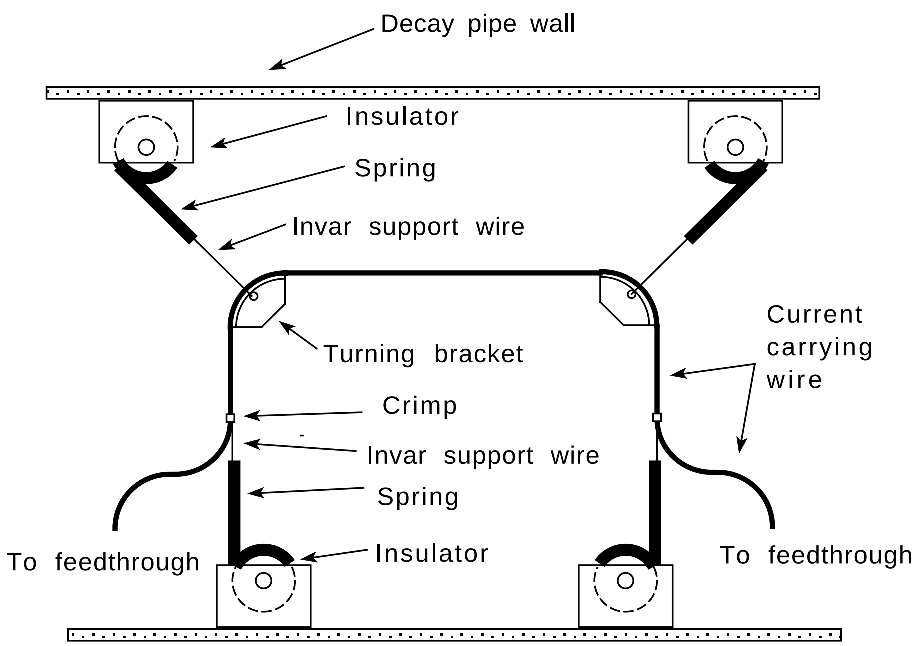

Figure 5: Schematic diagram, not to scale, of wire tensioning with springs.

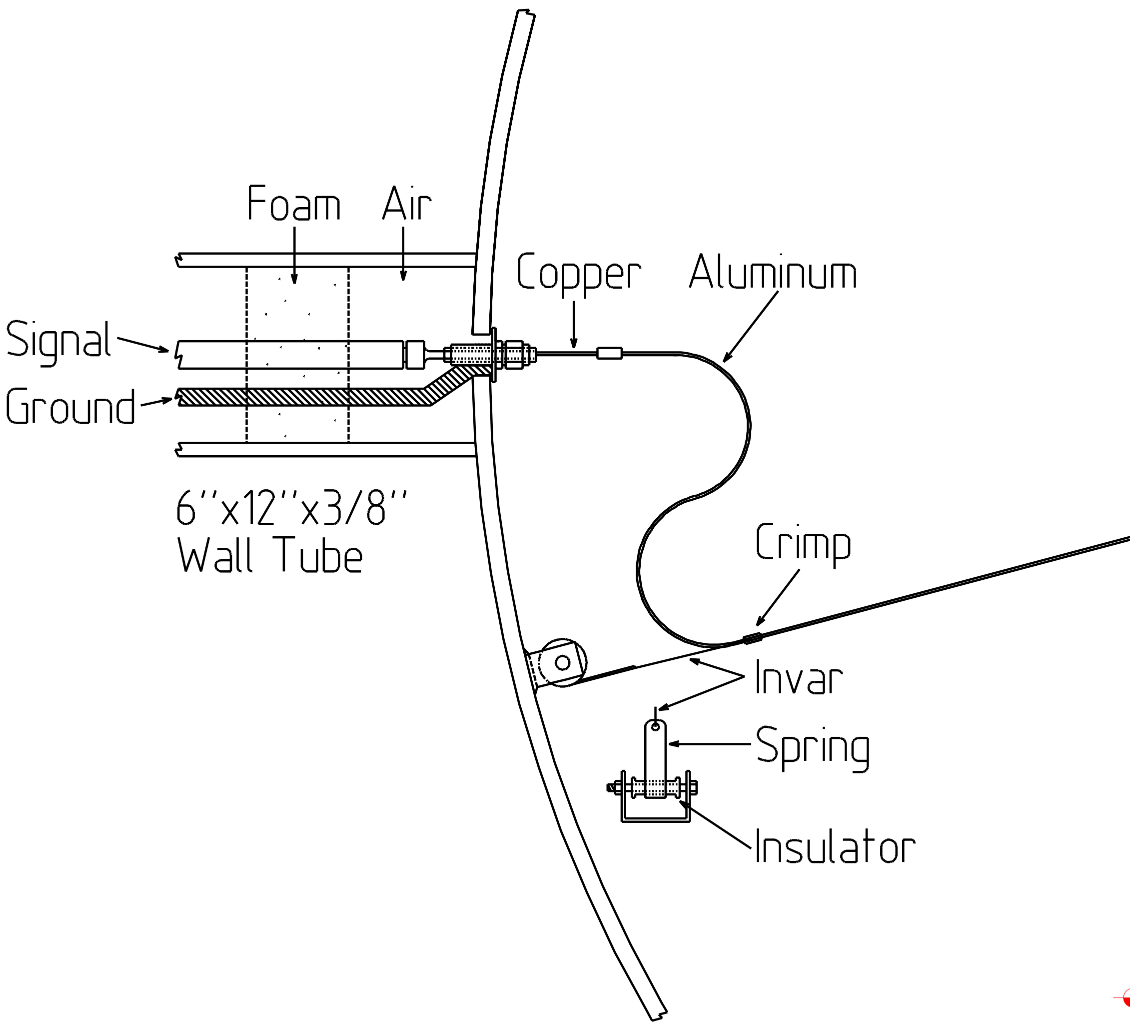

Figure 6: Vacuum feedthrough and wire support in decay pipe.

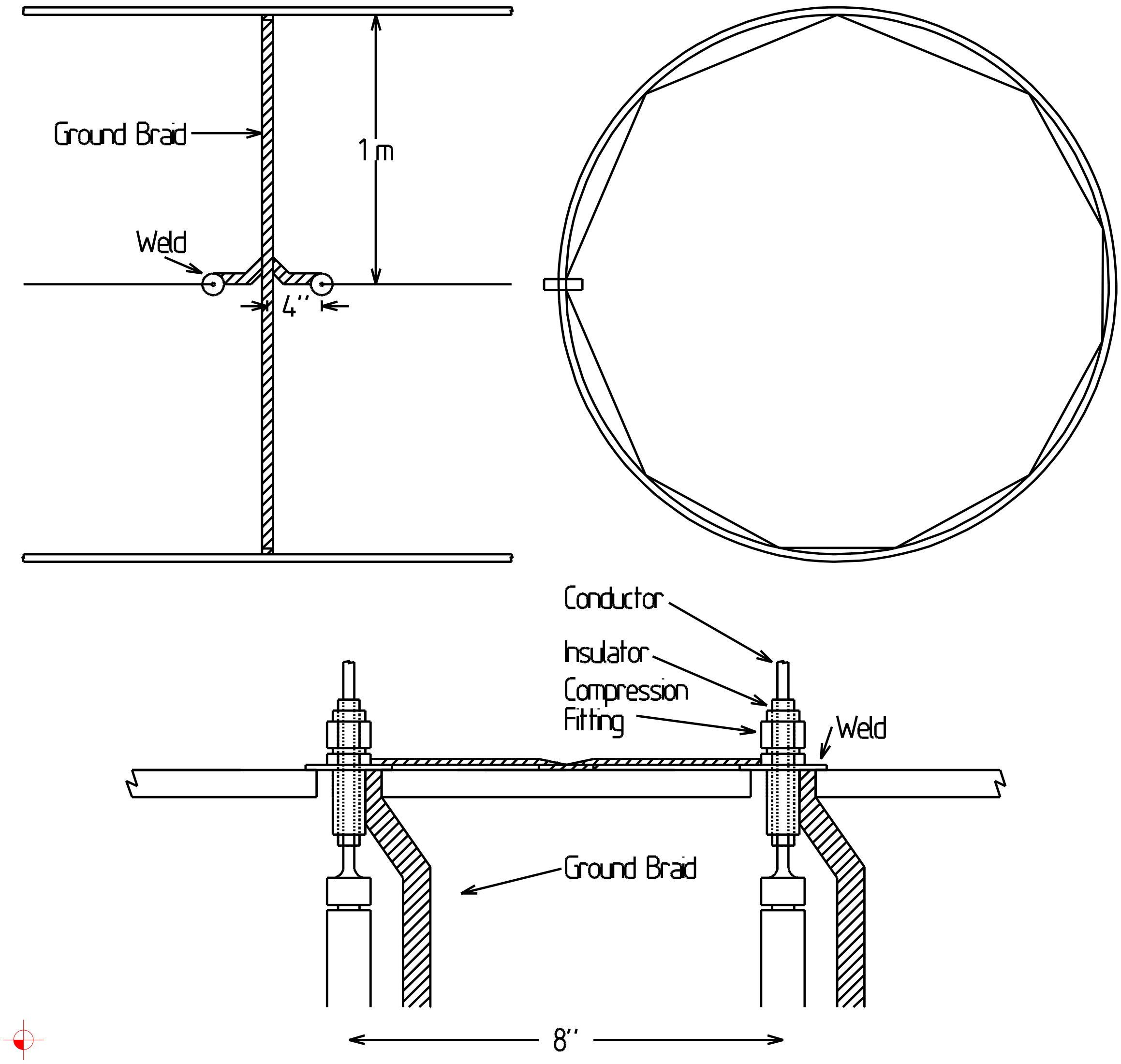

Figure 7: Feedthrough and internal ground strap in decay pipe.

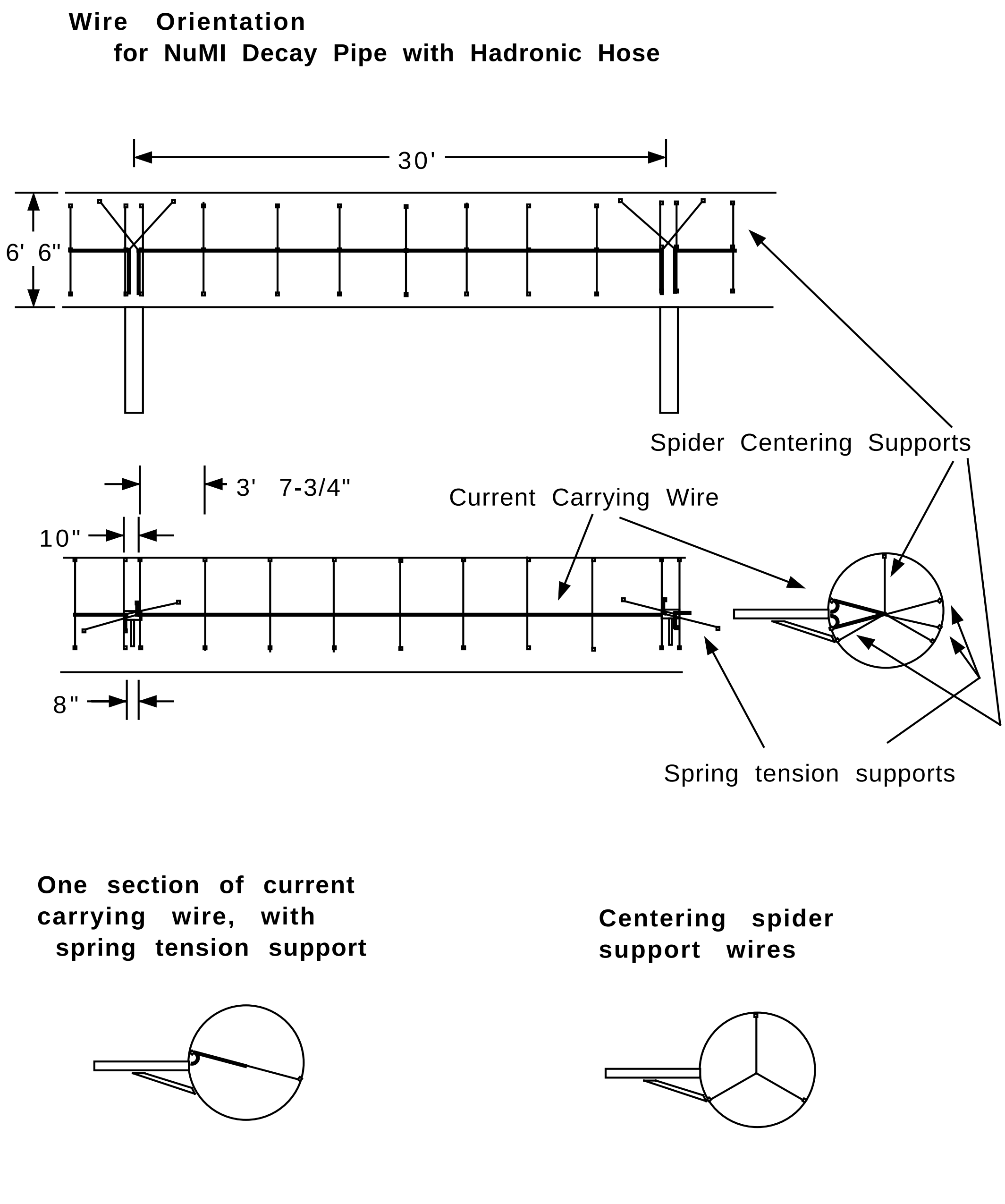

Figure 8: Orientation and support of hose wire in decay pipe.

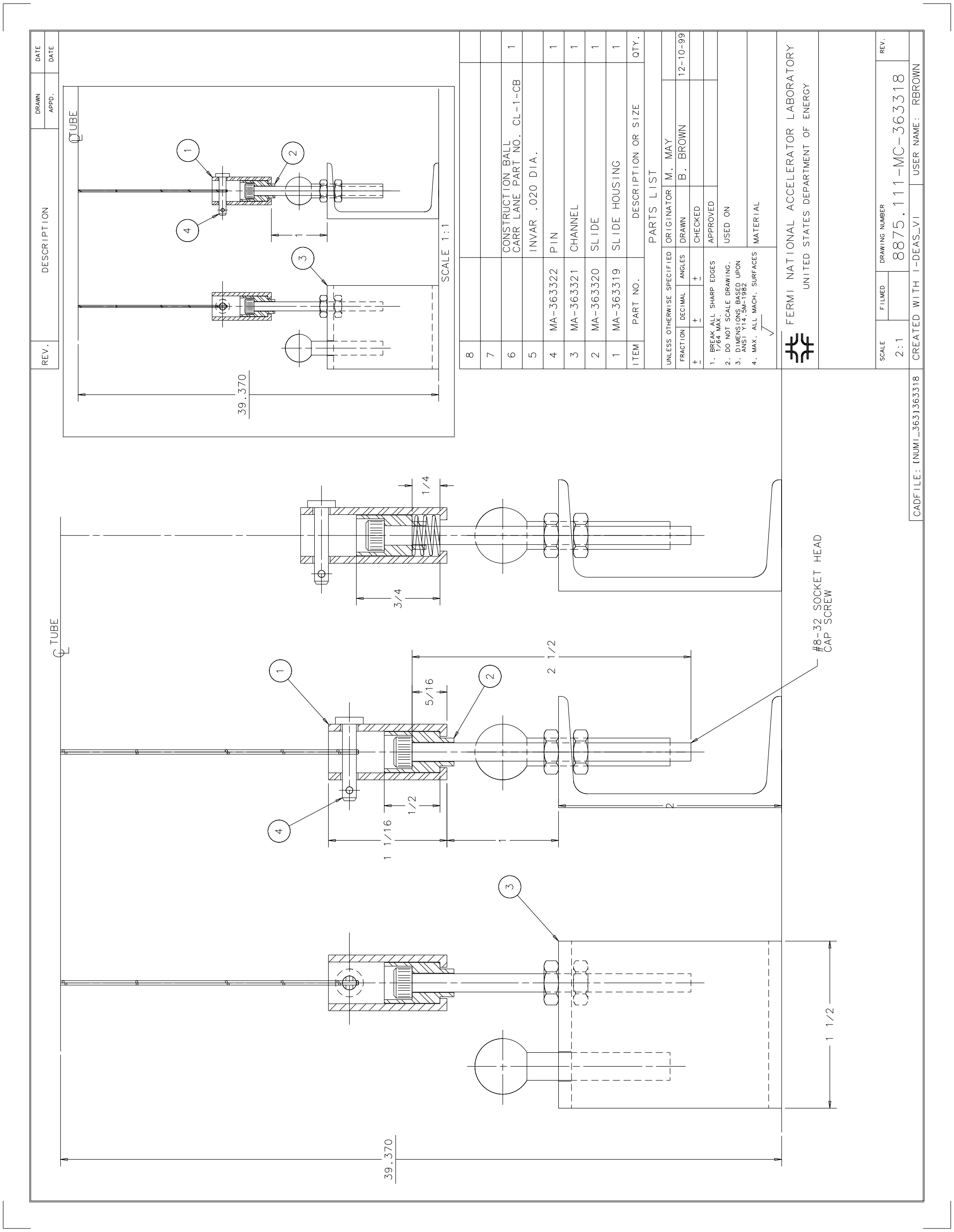

Figure 9: Bracket for spider support of hose wire.

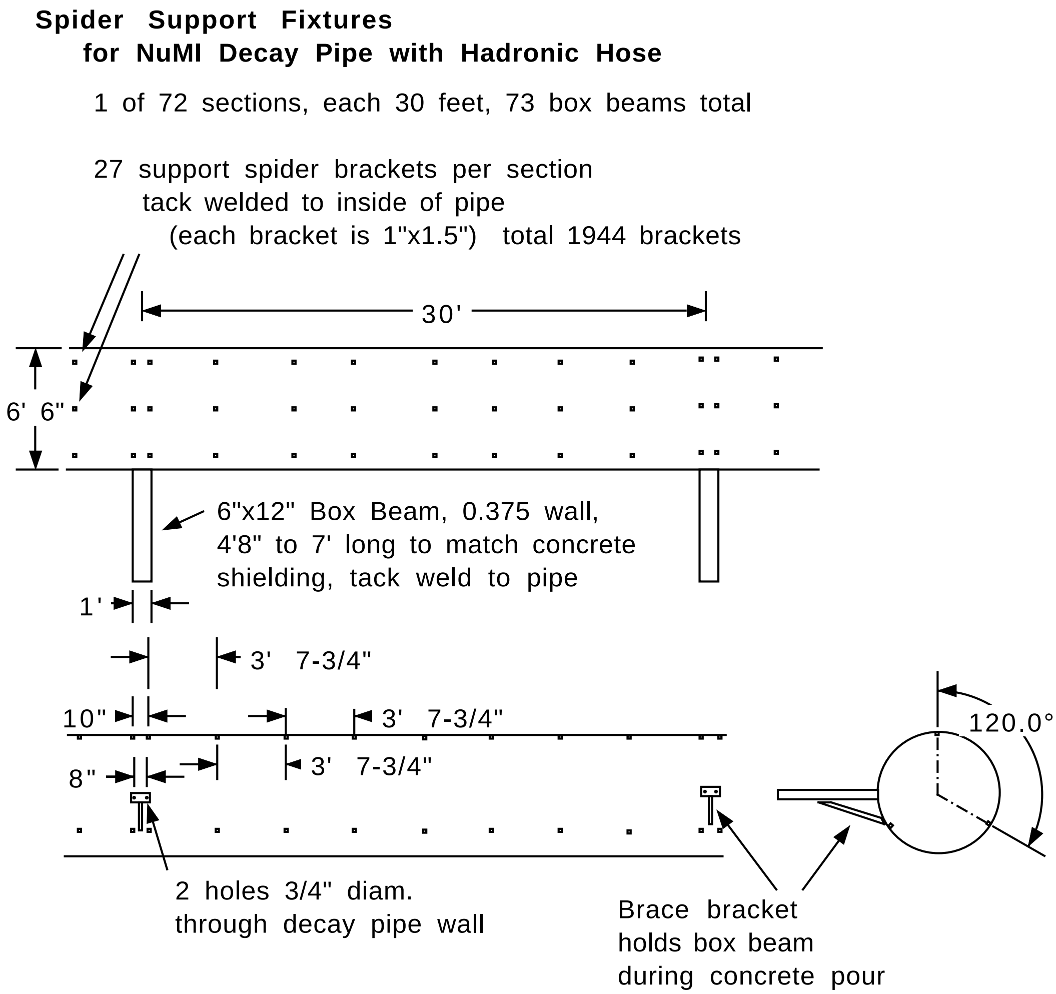

Figure 10: Locations for welding support brackets inside decay pipe.

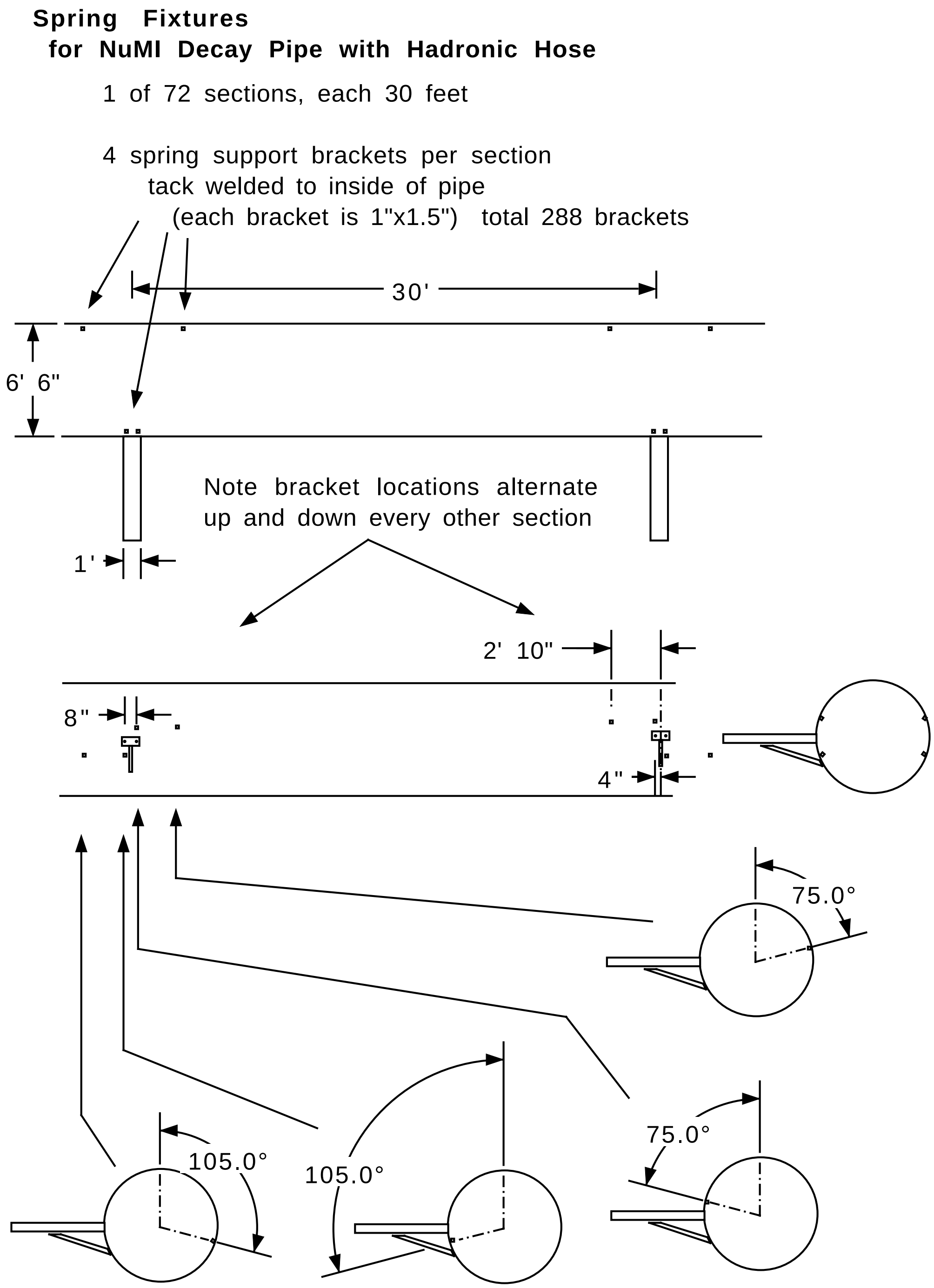

Figure 11: Locations for welding spring brackets inside decay pipe.

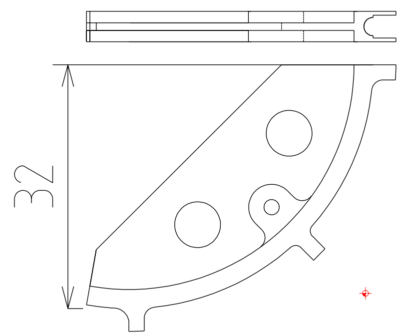

Figure 12: Hose wire turning bracket.

6 Power Supply and Distribution

The electrical scheme for powering the hadronic hose is shown in Figure 13.

A 100 μF capacitor bank is charged to 4 kV. An SCR is then fired to produce a 4 kA pulse to a stripline. The stripline feeds 72 transformers in series. The transformers have a 4:1 turns ratio, to produce 1 kA at 215 V for each hose segment. The resulting wave-form across a hose segment is shown in Figure 14. The pulse baseline is 319 μsec, and the current variation over a 10 μsec beamspill at the peak is only 0.15%.

Each hose segment has an inductance of 14 μH and resistance of 86 mΩ, which at the input to the transformer appears as 1 μH and 5 mΩ. The stripline impedence per segment is about an order of magnitude less than this.

The 46 milli-volt-second transformer core is of modest size, as shown in Figure 13. The secondary is 12 turns of #6 wire, the primary is foil wound.

Since these are pulsed transformers, with the pulse always in the same direction, a modest bias supply is required to reverse the field in the transformer core. This supply is protected from the main pulse by a large choke.

The space taken up by the capacitor bank, charging supply, and bias supply with choke, is estimated as 3 standard racks. This space appears to be available in the horn power supply room, but the hose power supply could also be located next to the absorber, by the decay pipe vacuum pumps.

The use of AL6201 wire instead of AL1350 will increase the maximum resistance of a segment from 86 milli-Ohm to 104 milli-Ohm.

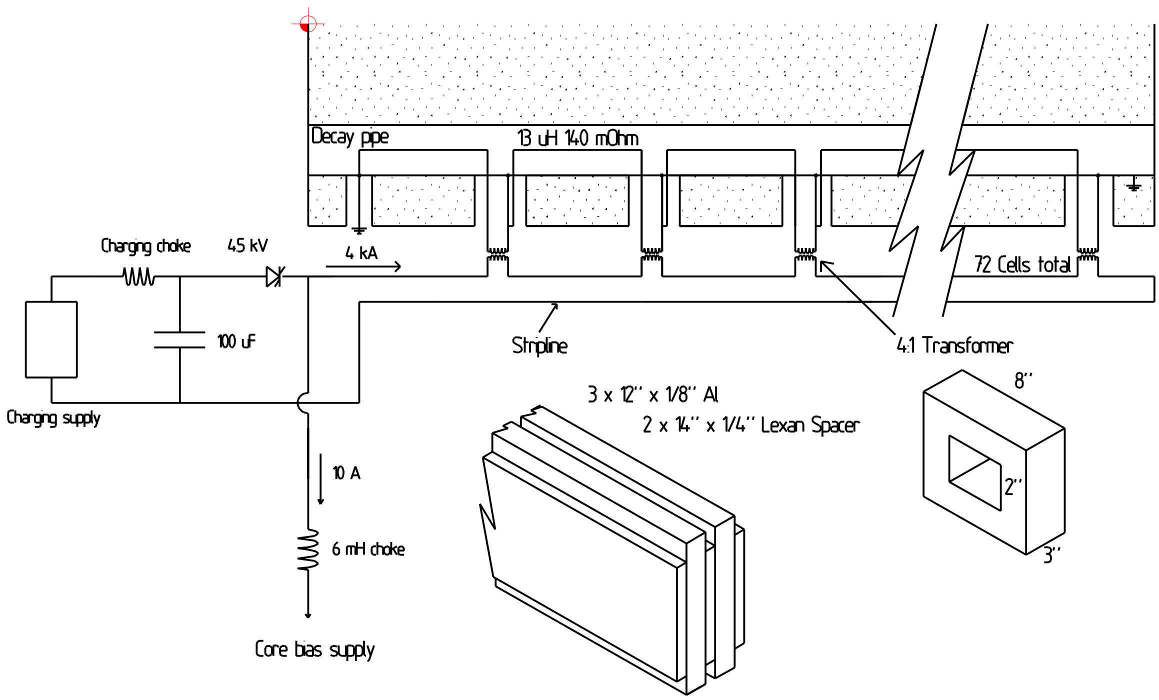

Figure 13: Hose electrical diagram, stripline and transformer core.

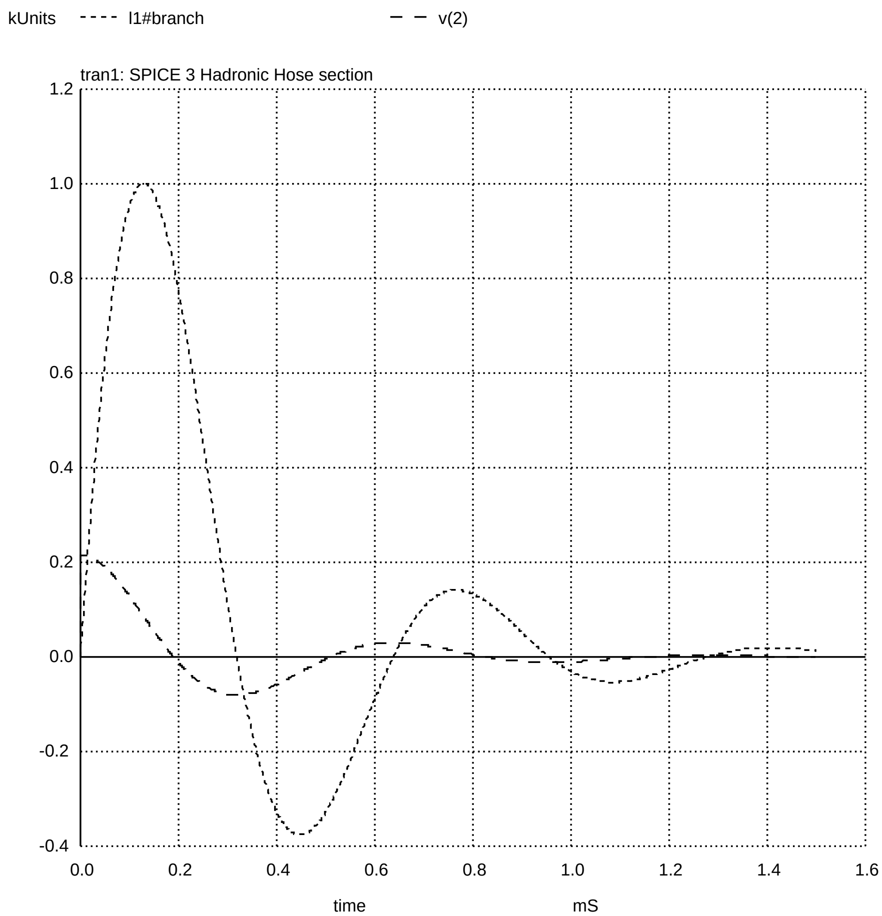

Figure 14: Current (kA, shorter dashes) and voltage (kV, longer dashes) waveforms for a segment of the hose calculated by SPICE computer code.

7 Survey and Alignment

The Hadronic Hose alignment goal is ± 2.0 mm maximum deviation of the central conductor from a straight line, which is set to minimize the intersection of particle orbits with the wire. (The alignment tolerance of this line to the direction of Soudan is considerably more relaxed). Every 1.11 m along the decay pipe, 3 brackets, spaced 120 degrees at 12, 4, 8 o'clock, will be welded to the inside of the pipe. Each bracket will have an attachment point for a radial support wire for the central conductor and a 1/4 inch diameter hole to insert a tooling ball for alignment. Before the decay pipe is installed, an alignment network will be setup in the tunnel. This will be needed both to correctly position the decay pipe and to increase the accuracy of the internal alignment network. After the decay pipe is in place and encased in concrete and before the central conductor is installed, a survey crew will start at one end and proceed internally down the pipe to the other end, measuring the location of a tooling ball in every bracket. It is estimated that 20 alignment crew shifts will be required to complete this. Pre-analysis shows that this would yield the tooling ball positions accurate to ± 4.0 mm (2 sigma) halfway along the decay pipe. If this internal network is tied through a power feed through port to the external network in the decay tunnel halfway down, this accuracy becomes ± 1.3 mm. To achieve more alignment tolerance safety factor, the internal network will be be tied to the external decay tunnel network at 3 places (1/4, 1/2, 3/4 points along the decay pipe) which would give an accuracy of 0.5 mm. As each 30 foot central conductor section is installed, it will be positioned by making stickmike measurements, accurate to 0.2 mm, to tooling balls in each of the three brackets at each position along the section.

8 Monitoring

The power supply will include voltage and current monitoring.

The current induced in each segment will be monitored by an induction pickup at the transformer output; the signal will be transmitted to the power supply room by an individual shielded wire pair. A cable tray is included in the decay pipe passage-way to hold these 72 cables.

The decay pipe RAW water system will include temperature, pressure, and flow monitoring. Makeup tank level will also be monitored, so that a leak could be detected.

Six thermocouples will be spaced along the decay pipe to monitor temperatures: three at the decay pipe wall and three in the passageway.

		Steel	Concrete		
			(0-30 cm)	(30-60 cm)	(>60 cm)
1	PH2L	62.7±0.5	42.9±0.2	6.14±0.01	2.89±0.00
2	PH2L HH	68.8±0.6	47.4±0.2	6.63±0.01	3.10±0.00
3	PH2L HH(2 mm)	68.7±0.5	47.5±0.2	6.73±0.01	3.12±0.00
4	PH2L BP	53.1±0.4	33.1±0.2	4.67±0.01	2.26±0.00
5	PH2L BP/HH	53.9±0.5	34.3±0.2	4.76±0.01	2.24±0.00
6	PH2L BP/HH(2 mm)	53.8±0.5	34.2±0.3	4.80±0.01	2.24±0.00
7	PH2M	65.3±0.5	46.2±0.3	6.99±0.01	3.26±0.00
8	PH2M HH	70.5±0.5	51.2±0.2	7.77±0.01	3.61±0.00
9	PH2M HH(2 mm)	69.8±0.5	50.6±0.2	7.56±0.01	3.62±0.00

Table 3: Total energy deposition in kW in the decay pipe steel and the concrete surrounding the decay pipe. Results are shown for simulations of: (1) the baseline low energy beam (PH2L), (2) the baseline low-energy beam including a perfectly aligned hadronic hose (HH), (3) low-energy beam including a hadronic hose aligned to 2 mm rms, (4) the low-energy beam with beam plug (BP) option, (5) the low-energy beam with beam plug option and a perfectly aligned hadronic hose, (6) low-energy with beam plug option including a hadronic hose aligned to 2 mm rms, (7) baseline medium-energy beam (PH2M), (8) medium-energy beam with perfectly aligned hadronic hose, (9) medium-energy beam with hadronic hose aligned to 2 mm rms.

Muon monitor chambers after the absorber, included in the NuMI baseline, are sensitive to the pulsing of the hose, and can be used as a pulse-to-pulse online monitor of its operation.

To allow the muon monitor chambers to also be sensitive to possible horn problems, the hose wire pulsing can be automatically inhibited for one pulse every few minutes. These non-hose pulses accumulated in the near detector over the course of a run will also provide a very interesting comparison data sample.

9 Decay Pipe Cooling

The amount of beam energy deposited in the decay pipe steel and in the concrete surrounding the decay pipe has been estimated from a series of MARS simulations for various beam configurations. Results are summarized in table 3, and the distribution along the length of the decay pipe is shown in Figures 15-17.

Beam heating of the decay pipe steel and concrete shielding reaches a max-

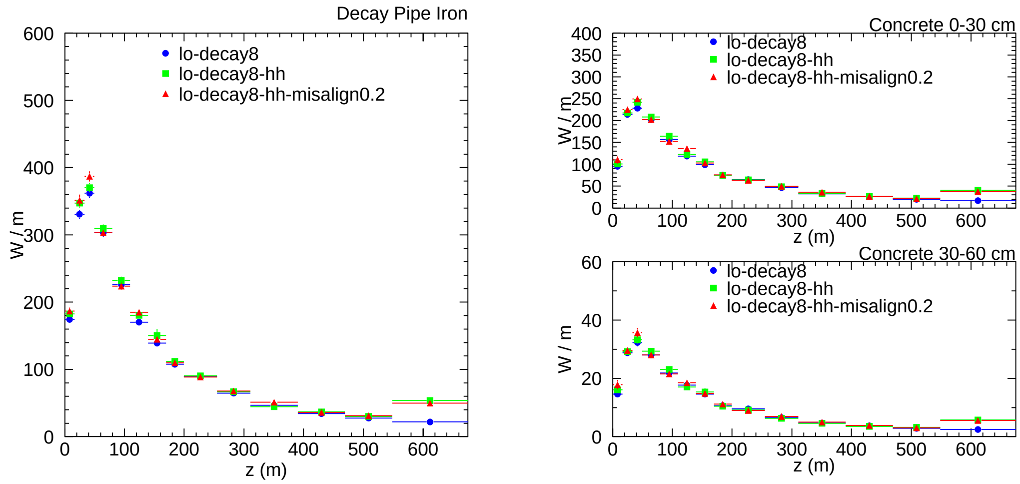

Figure 15: Energy deposistion in the decay pipe steel and in the concrete surrounding the decay pipe as a function of distance down the pipe for the baseline low-energy beam, baseline with hadronic hose option, and baseline with hadronic hose including simulated 2 mm wire misalignments.

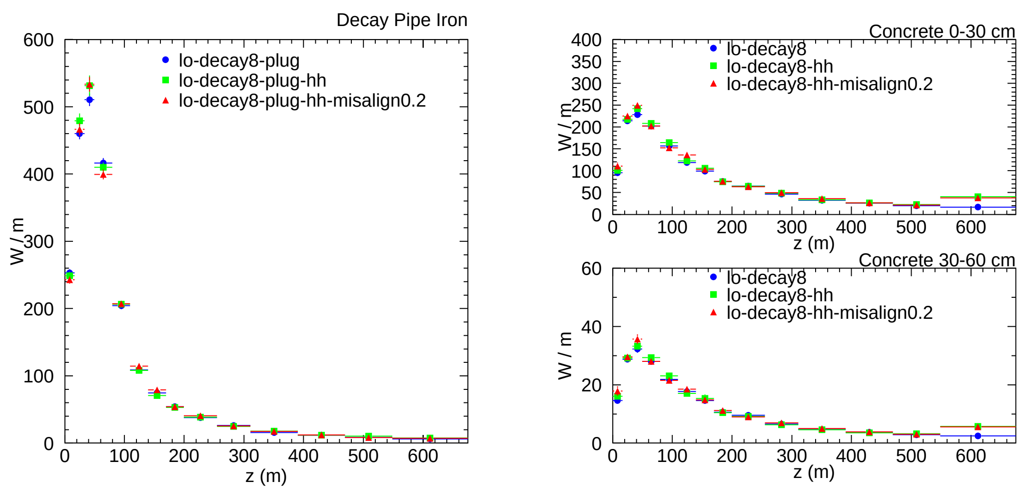

Figure 16: Energy distribution in the decay pipe steel and in the concrete surrounding the decay pipe as a function of distance down the pipe for the baseline+plug low-energy beam. Results from simulations including a perfect hadronic hose as well as a hadronic hose with simulated 2 mm wire misalignments are also shown.

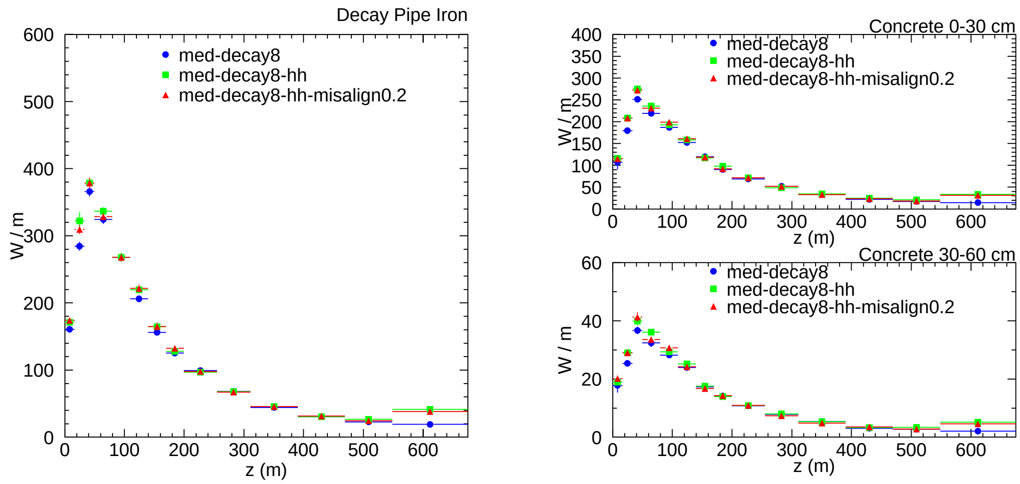

Figure 17: Energy deposition in the decay pipe steel and in the concrete surrounding the decay pipe as a function of distance down the pipe for the baseline medium energy beam, baseline plus hadronic hose, and baseline plus hadronic hose build with 2 mm wire misalignments.

imum of 700 W/m about 50 m into the decay pipe, although for most of the pipe it is an order of magnitude less than this. (If a beam plug is added, the total energy deposited in the decay pipe is reduced, but this local maximum is about 30% higher). In this hottest region, the concrete shielding is 2.13 m thick around the 1 m radius decay pipe. Making a simple and fairly good approximation that the heat is deposited at the wall, and using a thermal conductivity for concrete of k = 0.837 W/mC, the temperature drop through the concrete can be calculated as

$$\Delta T = \frac{P}{L}\frac{ln(R_o/R_i)}{2\pi k} = 152^{\circ}C$$

This is too high for reasonable reliable long term operation of the hadronic hose wire.

Running 12 1" nominal copper cooling pipes along the outside of the decay pipe, with the water flowing at 2.2 ft/sec, will remove the beam power while raising the water temperature by 5.6°C. The pipes should be as close to the steel as possible, with care to get good thermal contact.

Analytic estimates can be made as follows. If all the heat were assumed to be deposited in the 1/2" thick decay pipe steel, the maximum temperature difference between points farthest and closest to the cooling pipes is 6.5°C. (That is for 12 uniformly-azimuthally distributed pipes; if the pipes on the bottom needed to be twice as far apart to accomodate decay pipe structrual supports,

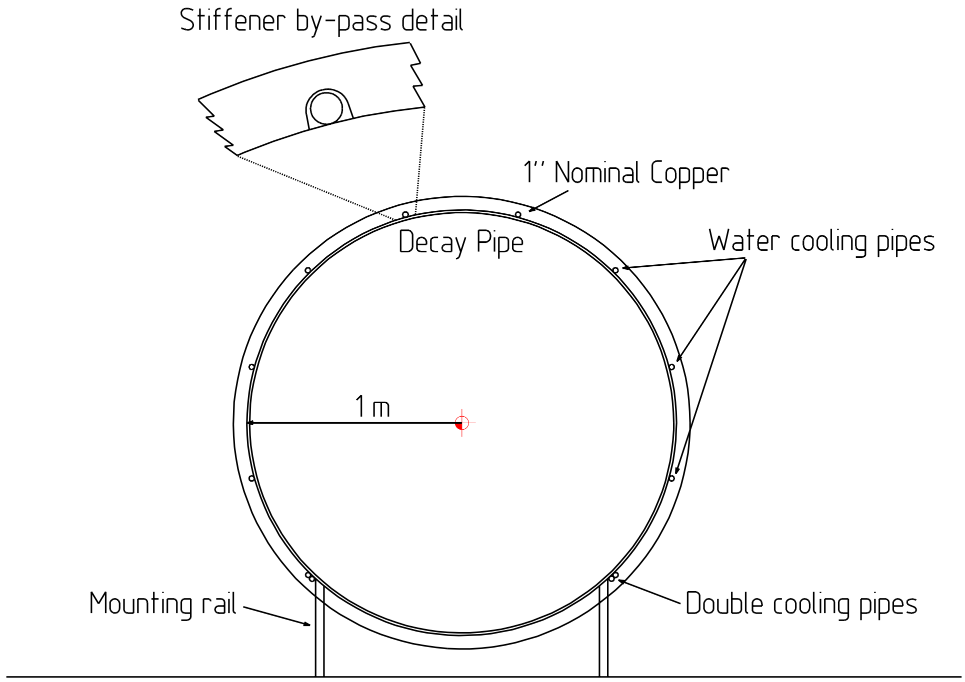

Figure 18: Copper pipes for water cooling of decay pipe steel.

then for that region the value quadruples to 26°C - see Figure18). Assuming no more than a 1mm air gap between concrete and steel, the maximum temperature on average between steel and concrete is only a couple degrees. With tight-packed cement making good contact to the copper pipe and the steel decay pipe, the temperature drop from decay pipe to copper pipe is estimated to be of order 20°C. Assuming 20°C cooling water entering the system, the average temperature of the decay pipe steel would then be around 50°C. 55°C has been used in the baseline beam wire heating calculations.

The major uncertainty is introduced by the possibility of air gaps in the concrete around the cooling line. A 1/2 mm air gap around the copper pipe would give another 15°C temperature rise. Such an increase could be safely absorbed by the baseline design. Local cooling could be improved by design modifications such as splitting into twice as many pipes in the 100 m region of highest beam heating. Copper tubing is routinely embedded in concrete for radiant panel heating in residential heating applications. Following guidencein ASHRAE Systems and Equiptment Handbook, the thermal resistance between the water and the surface of approximately 0.13 m^2K/W should result in a temperature gradient between the steel decay pipe copper tube of about 7.5°C. Since the Renolds number puts the flow in the turbulent regime, the temperature difference between the inner wall of the tube and the bulk water temperature is very small, less than 0.5°C. The total temperature difference between the hottest spot on the decay pipe and the inlet water temperature would then be about 20°C.

10 Installation

Installation is divided to two phases: contractor installation before beneficial occupancy and FNAL installation after that.

The installation steps in this scenerio are arranged to put all welding in the contractor phase, when ventillation and power are aready set up for welding, and when it is only necessary to go short distances into the decay pipe for installation. Internal bracket welding, Steps 3 v-vi, may also be moved to Step 6.

Step 7, doing a pump down test of the entire vacuum pipe, is now considered probably unnecessary.

The impact of the hose on the overall NuMI schedule is not yet very clear, since the hose tasks have not been discussed with the contractor. The installation of cooling pipes along the decay pipe may well have non-negligible schedule implications, depending on exactly how the contractor gets the work done. The installation of the hose wire in the decay pipe and the electrical components in the decay pipe passage-way should have small impact since they can be done in parallel with target pile installation.

	Contractor
1	*dig tunnel*
2	*contractor survey to 1 cm, tells where to put decaypipe to 2 cm*
3	for each 30 foot section:
i	*install 30 feet of decay pipe / weld*
ii	locate where to drill holes: $<$ 2cm
iii	locate where to put internal brackets: $<$ 2cm
iv	drill holes / face off
v	weld internal brackets
vi	weld internal ground strap
vii	weld feed-thru decay pipe
viii	leak test with dye penetrant, vacuum box
ix	weld feed-thru pipe to decay pipe
x	weld feed-thru support bracket to decay pipe
4	install water cooling pipes
5	pour concrete
	Beneficial Occupancy
6	install feed-thru wires, brackets, if not already done
7	install vacuum window / pump down test / take off window ?
8	survey internal bracket locations: 0.2mm local / 2mm global
9	stockpile wires at ends of decay pipe
10	starting in middle, install hose. For each 30 foot section:
i	install bracket adjustment parts
ii	carry in hose wire with spider wires attached
iii	hook up top spider attachments
iv	hook up feedthru and spring tension attachments
v	hook up bottom spiders checking stick mic for adjustment
vi	electrical test of section
11	install vacuum window
12	install stripline, transformers

Table 4: Installation steps. *Italics: needed even without hose* .

11 ES&H Considerations

There are several ES&H issues to be considered during the installation and testing of the hadronic hose.Assuming that the configuration and radiological conditions would preclude any access to the hadronic hose for maintenance or repair once NuMI operations have begun, the only ES&H considerations during operations would be the impact on production of residual radioactivity. This is discussed in Appendix B.

The NuMI decay pipe will be a confined space, as defined in the Fermilab ES&H Manual. As a general rule, any work that can be performed outside of the decay pipe, preferably on the surface, should be done there to minimize the man-hours inside the pipe. Whether or not a confined space at Fermilab requires a permit for entry depends on whether it may contain a hazardous atmosphere or similar hazards. If the welding necessary for the hadronic hose installation is done during construction of the decay pipe, i.e., towards the ends of the pipe segments before it is a confined space, then there are no evident atmospheric hazards and the decay pipe would probably not be a permit-required confined space. The Beams Division ES&H Dept. would have to make the final determination on whether a permit is required or not. In any case, supplemental ventilation will probably be necessary to provide adequate fresh air for workers inside the decay pipe.

The decay pipe is likely to be a noisy environment. The combined effects of using power tools in a confined space, the surrounding steel surface, the supplemental ventilation and airflow over the installed wires might produce an ambient noise level that would require hearing protection.

Communication from inside the decay pipe will require that a phone line or possibly a long radio antenna be run to the regions where work is taking place. Additional cables for lights and electric power will be needed. Electrical safety inside the steel pipe will require that these be properly grounded in common with the decay pipe. Power supplies for the hadronic hose should be locked out while workers are inside the decay pipe.

Finally, the ergonomics of working inside the decay pipe will probably be poor. The floor will be neither flat nor level, with travel possible in only one direction. The humidity is likely to be high, possibly leading to condensation on the inner surface of the decay pipe. With these factors, combined with the presence of the hadronic hose support wires and the necessary cables run in for the work, the slip and trip hazards are likely to be well above normal, with medical assistance considerably farther away. These hazards could be mitigated to some extent, and the installation process made more efficient, by having a mock-up of a section of the decay pipe to use for working out the procedures and training the work crews.

12 Cost Estimate

The total cost estimate for the hadronic hose is $1,936,453, which breaks down as follows:

- Construction of the hose proper is estimated at $1,045,631 plus contingency of $312,604.
- A system to water cool the decay pipe region, which may not be needed if the hose is not constructed, is an additional $231,863 plus $67,375 contingency.
- A program of R&D, including the construction of a full scale prototype section, is estimated at $214,600 plus $64,380 contingency.

WBS 1.1, NuMI Technical Components, currently has 8 levels; thus hadronic hose is proposed as WBS 1.1.9. Figure 19 shows the labor rates used in the cost estimate. An additional cost penalty of 25% is added to all underground labor, to take account of inefficiencies caused by the location of the work.

Figure 20 gives an overview of the costs by WBS element; details of each cost element are given in Figures 21-29.

To understand various possible funding scenerios, the cost is divided into three pieces as follows:

- The items which, while necessary to hadronic hose operation, could be deferred until after NuMI construction and added at a later time. These are mainly power supply and electrical system components, and are marked in Figures 21-29 by shaded boxes in the 'Total's columns. The total that can be deferred is $616,655.
- Items which can be put "off budget", i.e. not require explicit WBS funding. These are mainly machine shop time at UTA, part of the R&D done at universities, and physicist time. These items are repeated in a separate column in Figures 21-29. The total that can be thus "provided by others" is $260,153.
- The items for which funding must be found to not preclude installation of the hadronic hose. This amount is $1,059,645, which includes contingency and $158,600 of R&D.

LABOR RATES		
TYPE	DESCRIPTION	$ PER HR
AC or AF	Surveyor	40.00
DR	Drafter	40.00
DS	Designer	45.00
EN	Engineer	60.00
ET	Electrician	60.00
LB	Laborer	40.00
MC	Mason/Concrete Worker	40.00
PH	Physicist	60.00
PF	Plumber/Fitter	60.00
SC or SF	Shops - Contract/Fermi	55.00
TB or TC	Technician - Beams/Contract	35.00
WC	Welder	60.00

Down Hole Penalty is the Indicated Percentage at Right Applied to Task Labor Cost to Reflect Inefficiency of Worker in Below Ground Enclosure.	**25%**

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Figure 19: Labor rates for cost estimate for hadronic hose.

NuMI HADRONIC HOSE COST ESTIMATE SUMMARY

WBS	DESCRIPTION	M&CS	LABOR	M&CS + LABOR	DOWN HOLE PENALTY	TOTAL	CONTINGENCY	
1.1.9.1	Modifications to Civil 6-7-4	109,759	111,330	221,089	27,833	248,921	30%	74,676
1.1.9.2	Decay Pipe LCW Cooling System	43,672	0	43,672	0	43,672	25%	10,918
1.1.9.3	HH Wire-Supports-Feedthrus	102,227	49,665	151,892	0	151,892	20%	30,378
1.1.9.4	Power Supply	282,071	0	282,071	0	282,071	35%	98,725
1.1.9.5	Electrical Service	39,453	88,570	128,023	22,143	150,166	30%	45,050
1.1.9.6	Research and Development	90,000	124,600	214,600	0	214,600	30%	64,380
1.1.9.7	Installation	33,000	174,942	207,942	43,736	251,678	30%	75,503
1.1.9.8	Survey	0	24,700	24,700	6,175	30,875	30%	9,263
1.1.9.9	EDI&A	0	118,220	118,220	0	118,220	30%	35,466
	TOTALS	**700,182**	**692,027**	**1,392,209**	**99,886**	**1,492,094**		**444,359**

WBS TOTALS PLUS CONTINGENCY: **1,936,453**

WBS	DESCRIPTION	DEFERRED	CONTINGENCY DEFERRED	TOTAL DEFERRED	PROVIDED BY OTHERS	CONTINGENCY PROV BY OTHRS	TOTAL PROVIDED BY OTHERS
1.1.9.1	Modifications to Civil 6-7-4	0	0	0	730	219	949
1.1.9.2	Decay Pipe LCW Cooling System	0	0	0	0	0	0
1.1.9.3	HH Wire-Supports-Feedthrus	0	0	0	50,687	10,137	60,824
1.1.9.4	Power Supply	277,538	97,138	374,676	0	0	0
1.1.9.5	Electrical Service	140,128	42,038	182,166	0	0	0
1.1.9.6	Research and Development	0	0	0	92,600	27,780	120,380
1.1.9.7	Installation	1,050	315	1,365	30,000	9,000	39,000
1.1.9.8	Survey	0	0	0	30,000	9,000	39,000
1.1.9.9	EDI&A	44,960	13,488	58,448	0	0	0
	TOTALS			**616,655**			**260,153**

WBS TOTALS PLUS CONTINGENCY MINUS TOTAL DEFERRED: **1,319,799**

MINUS TOTAL PROVD BY OTHERS: **1,059,645**

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Figure 20: WBS cost estimate rollup for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.1

COMPONENT or WBS DESCRIPTION: Modifications to Civil 6-7-4

NAME: May and Ducar

PHONE & MAIL STOP:

ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.1-1	Provide 12 ~1.25" Slots in Decay Pipe Strength Ribs. 150 Ribs	EE	Rib	150		60.00	9,000					0		0			
1.1.9.1-2	1" Copper Pipe, Type K, 122 Alloy, .065" Wall, 1.125" OD, .995" ID, 12 Runs Longitudinally Along Decay Pipe. 0.839 lb per Foot. 22,351 lbs. 26,640 Feet Required.	VQ	60'Coil	444		102.81	45,648					0		0		15% Above Vendor Quote	
1.1.9.1-3	Couplings for 1" Copper Pipe	CP	Each	432		0.75	324					0		0			
1.1.9.1-4	End Caps for 1" Copper Tubing	EE	Each	24		1.00	24					0		0			
1.1.9.1-5	Install Copper Pipe Onto Decay Pipe. 37 x 60 Foot Sections and 12 Pipes per Section. At 3 Hours x 37 Sections.	EE					0		3	PF	111	333	60.00	19,980	4,995		
1.1.9.1-6	Flatten Copper Pipe After Installation Onto Decay Pipe. 37 x 60 Foot Sections and 12 Pipes per Section. At 2.5 Hours x 37 Sections.	EE					0		3	PF	93	278	60.00	16,650	4,163		
1.1.9.1-7	Silfloss 37 Sections Copper Pipe Together and 24 x End Caps. 38 Places and 12 Circumfrential Solder Joints per Place. 4 Hours per Place.	EE					0		2	PF	152	304	60.00	18,240	4,560		
1.1.9.1-8	Drill 144 Pilot Holes on Outside of Decay Pipe for Electrical Feedthrus. 8" Spacing, 30' Intervals.	EE					0		2	LB	72	144	40.00	5,760	1,440		
1.1.9.1-9	Box Beam, Steel, 6" x 12", 0.375 Wall. 6+ Feet Long	EE	Each	73		260.00	18,980					0		0			
1.1.9.1-10	Machine End of Box Beam to Decay Pipe Curvature	EE	Each	73		40.00	2,920					0		0			
1.1.9.1-11	Steel 1" Angle to Support Box Beam. Cut to Correct Length.	EE	Each	73		20.00	1,460					0		0			
1.1.9.1-12	Weld Box Beam to Decay Pipe at 30 Foot Intervals. 73 Places	EE					0		2	WC	73	146	60.00	8,760	2,190		
1.1.9.1-13	Polyester Strapping to Hold Copper Pipe in Place Between Ribs. 1 Foot Intervals. 1/2 Wide, 10,500 Feet per Roll Granger #5W148	CP	Roll	5		134.65	673					0		0			
1.1.9.1-14	Heat Sink Compound for Application Between Copper Pipe and Decay Pipe.	EE	Cartridge	200		25.00	5,000					0		0			
1.1.9.1-15	Apply Heat Sink Compound Between Copper Pipe and Decay Pipe. 2 Hours per 30 Foot Segment	EE					0		2	LB	144	288	40.00	11,520	2,880		
1.1.9.1-16	Labor to Install and Tighten Pipe Strapping at 1 Foot Intervals. 2 Hours per 30 Foot Segment.	EE					0		2	LB	144	288	40.00	11,520	2,880		
1.1.9.1-17	Box Out Concrete Form for Box Beam Penetration. 73 Places.	EE					0		2	MC	110	219	40.00	8,760	2,190		
1.1.9.1-18	Bore Additional 24" Diameter 30 Foot Long Penetration from Horn Power Supply Room to Target Hall for HH Wire PS Stripline and Miscellaneous Cabling. Penetration to be Lined with Steel Pipe and Grounded.	SWAG	Each	1		25,000.00	25,000					0		0			
1.1.9.1-19	Enlarge Area of Horn PS Room to Accommodate HH Wire PS.	WAG	Each	1		30,000.00	0					0		0		Deleted From Scope	
1.1.9.1-20	Pneumatic/Hydro Test Installed Copper Pipe	EE					0		2	PF	48	96	60.00	5,760	1,440		
1.1.9.1-21	Installed 2 Ton Chain Fall to Facilitate Placement of Decay Pipe Flanged End Bells.	EE	Each	2		5,000.00	0					0		0		Deleted From Scope	
1.1.9.1-22	Copper Grounding Plate With Tapped Holes and Plated Surface for Ground Connection Between Wire Feedthru at Exterior of Decay Pipe.	EE	Each	73		10.00	730					0		0			730
1.1.9.1-23	Silfloss Grounding Plate to Decay Pipe Exterior. 73 Places.	EE					0		2	WC	37	73	60.00	4,380	1,095		
			TOTAL MATERIALS & SERVICES				109,759	TOTAL LABOR						111,330	27,833	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											221,089			730

TECHNICAL DESCRIPTION:

The above work relates in part to installation of cooling pipes along the length of the decay pipe.

When installed, the holes in the strength ribs must align with each other to facilitate installation of piping. Strength ribs must also be placed such that they are completely clear of access ports.

Pilot holes for HH Wire feedthrus must be drilled before placement and welding of the box beam to the decay pipe. It is thought that these holes are best drilled from the outside of the decay pipe.

Box beam tubes should extend out a minimum of 2 inches beyond formed concrete outside finished surface.

Grounding Strap Attached to Grounding Plate (ref. Item 1.1.9.1-23) Before Installation and Welding of Box Beam to Outer Decay Pipe Wall.

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

Assume Strength Ribs Every ~15 Feet for a Total of 150 Ribs.

Assume 30 Foot Long Hadronic Hose Sections for a Total of 72 Segments.

Hadronic Hose Power Supply is Expected to Fit in Horn Power Supply Room.

VQ for 1.1.9.1-2 by Copper and Brass Sales, Bob Miller 847-774-5798, is Pending.

VQ for 1.1.9.1-2 by Marco Supply Co., Chicago IL, Kristen/Ronnie 773-927-2427 at $1.49 per Foot or $39,694 Total. Price Shown is Increased by 15% to Accommodate Copper Price Escalation.

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Figure 21: WBS element 1.1.9.1 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.2
COMPONENT or WBS DESCRIPTION: Decay Pipe LCW Cooling System

NAME: Puska and Ducar
PHONE & MAIL STOP:
ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.2-1	Upstream End Manifold, 2" Type K Hard Copper. Installed.	EE	Each	1		7,500.00	7,500					0		0			
1.1.9.2-2	Downstream End Manifold, 2" Type K Hard Copper. Installed.	EE	Each	1		7,500.00	7,500					0		0			
1.1.9.2-3	75 KW Heat Exchanger. One at Each End. Installed.	EE	Each	2		5,400.00	10,800					0		0			
1.1.9.2-4	10 HP LCW Pump. One at Upstr End and One at Dwnstr End.	CP	Each	2		3,436.00	6,872					0		0			
1.1.9.2-5	Resovoir/Expander Tank at Downstream End of Decay Pipe. Installed.	EE	Each	1		1,500.00	1,500					0		0			
1.1.9.2-6	Connection to Upstairs Distilled Water Source for Process Water. Installed.	EE	Each	1		5,000.00	5,000					0		0			
1.1.9.2-7	Process Water Filters. Installed.	EE	Each	2		2,250.00	4,500					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
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							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
			TOTAL MATERIALS & SERVICES				43,672	TOTAL LABOR						0	0	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											43,672			0

TECHNICAL DESCRIPTION:

Rather than provide a RAW system for cooling, it is assumed that the cooling water inventory will be dumped to enclosure sump pumps before tritium concentration exceeds surface discharge limits. Make up distilled water is provided via a pipe connection to the surface at the MINOS service building.

Initial assessments of induced radioactivity in process water indicate that draining and replenishment of the system should conservatively occur at three month intervals during optimum running conditions.

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

Assume Strength Ribs Every 15 Feet for a Total of 150 Ribs.

Twelve 1 Inch Copper Pipes Run the Full Length of the Decay Pipe for Cooling. See 1.1.9.1 Cost Estimate Sheet.

Assumed This Cooling System is Operational Before Decay Pipe is Subject to Significant Heating.

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Figure 22: WBS element 1.1.9.2 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.3

COMPONENT or WBS DESCRIPTION: HH Wire - Supports - Feedthrus

NAME: May and Ducar

PHONE & MAIL STOP:

ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.3-1	Hadronic Hose Wire. 6201 T81 Al Alloy. 2.4mm (.095 Inch) Diameter	A00	Pounds	100		12.00	1,200					0		0			
1.1.9.3-2	Anodize Hadronic Hose Wire.	EE	Lot	1		1,000.00	1,000					0		0			
1.1.9.3-3	Wire Prep - Cut into Seventy-Two 38 Foot Lengths and Straighten.	EE					0	Mech Tech	2	TB or TC	40	80	35.00	2,800			2,800
1.1.9.3-4	Prepare Wire Ends (Scrape Off Anodize - Silver Plate)	EE					0	Mech Tech	2	TB or TC	60	120	35.00	4,200			4,200
1.1.9.3-5	HH Wire Bending Fixture	EE	Each	1		500.00	500					0		0			
1.1.9.3-6	Wire Tensioning End Bracket (from Harvard). Four per Segment.	VQ	Each	288		10.00	2,880					0		0			2,880
1.1.9.3-7	Ceramic Insulators for Spider and Tensioning Spring Supports.	EE	Each	2,232		12.00	26,784					0		0			
1.1.9.3-8	Insulated Spider Support Assembly. 27 Required per Segment. Excludes Insulator. Includes Tooling Balls, Misc Materials, Some Machining, and Assembly.	EE	Each (Misc Matl)	1,944		15.00	29,160	Mech Tech	1	TB or TC	324	324	35.00	11,340			11,340
1.1.9.3-9	Tensioning Spring. 5/8" Wide. 4 Required per Segment.	A00	Each	288		6.85	1,973										
1.1.9.3-10	Insulated Tensioning Spring Support Assembly. 4 Reqd per Segment. Excludes Insulator. Includes Misc Materials, Some Machining, and Assembly.	EE	Each (Misc Matl)	288		15.00	4,320	Mech Tech	1	TB or TC	72	72	35.00	2,520			2,520
1.1.9.3-11	Invar 36 Support Wire. .020 Inch Diameter. ~18,000 Foot Reel, 19.7#	A00	Reel	3		400.00	1,200					0		0			
1.1.9.3-12	Spider Support Invar Wire Bending Fixture	EE	Each	1		250.00	250					0		0			
1.1.9.3-13	Spider Assembly Prior to Installation. Assy Rate of 8 per Hour.	EE					0	Mech Tech	1	TB or TC	243	243	35.00	8,505			8,505
1.1.9.3-14	HH Wire Assembly Prior to Installation. Assy Rate of 2 Hours Each.	EE					0	Mech Tech	2	TB or TC	144	288	35.00	10,080			
1.1.9.3-15	Fixture for Spotting Spider Supports	EE	Each	1		2,000.00	2,000					0		0			2,000
1.1.9.3-16	Fixture for Spotting Tensioning Sring Supports. Attach to Above.	EE	Each	1		750.00	750					0		0			750
1.1.9.3-17	HH Copper/Ceramic Feedthru Assembly Including Two Copper Solder Adapters.	EE	Each	144		95.00	13,680					0		0		15% by Others	2,052
1.1.9.3-18	Stripline Copper Conductors for Interior of Box Beam. Two HH Wire Conductors Plus Ground Conductor. Includes Dielectric Spacers and Kapton Wrap. Plated Ends at Connection Points. One Assembly Per Box Beam. Approximately Six Feet Long.	EE	Each (Misc Matl)	73		70.00	5,110	Elec/Mech Tech	2	TB or TC	146	292	35.00	10,220			10,220
1.1.9.3-19	Strapping Hardware to Hold Stripline Together in Box Beam.	EE	Each	73		25.00	1,825					0		0			1,825
1.1.9.3-20	Cut Foam Inserts for Box Beams. 2 Per Box Beam.	EE	Each	146		7.50	1,095					0		0			1,095
1.1.9.3-21	Poly Beads to Fill Box Beam Tubes. 225 Cu Ft Required.	EE	Gaylord	8		1,000.00	8,000					0		0			
1.1.9.3-22	Fixture to Adapt Magnetic Base Drill to Inner Decay Pipe Wall	EE	Each	1		500.00	500					0		0			500
							0					0		0			
			TOTAL MATERIALS & SERVICES				102,227	TOTAL LABOR						49,665	0	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											151,892			50,687

TECHNICAL DESCRIPTION:

HH wire segments are fully prepared and shaped prior to installation.

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

Assume 30 Foot Hadronic Hose Sections for a Total of 72 Segments.

3 Point HH Wire Spider Supports are Spaced at 3 Foot 8 Inch Intervals Along Each Segment. Nine Spider Supports per Segment.

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Figure 23: WBS element 1.1.9.3 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.4
COMPONENT or WBS DESCRIPTION: Power Supply

NAME: Pfeffer and Ducar
PHONE & MAIL STOP:
ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.4-1	Hadronic Hose Wire Power Supply. 4.5 KV 4000A 300 Microsecond Half Sine Wave.	EE *1.5	Each	1		37,500.00	37,500					0		0		Defer	
1.1.9.4-2	Transformer for Connection to HH Wire Segments. Potted. Supplied with Appropriate Fixturing for Direct Mount to Concrete Wall.	EE * 1.5	Each	72		1,500.00	108,000					0		0		Defer	
1.1.9.4-3	Aluminum Conductor for Stripline. 12 inches Wide by 0.125 Inch Thick.	EE	Foot	7,200		2.50	18,000					0		0		Defer	
1.1.9.4-4	Lexan Dielectric for Stripline. 14 inches Wide by 0.125 Inch Thick.	EE	Foot	4,800		2.75	13,200					0		0		Defer	
1.1.9.4-5	Stripline Clamps	EE	Lot	1		10,000.00	10,000					0		0		Defer	
1.1.9.4-6	Stripline Assembly	EE	Lot	1		30,000.00	30,000					0		0		Defer	
1.1.9.4-7	Strongback for Transporting 30 Foot Stripline Segments	EE	Each	1		1,500.00	1,500					0		0		Defer	
1.1.9.4-8	Flexible Jumpers Connecting Stripline Inner Conductor to Transformer	EE	Each	146		50.00	7,300					0		0		Defer	
1.1.9.4-9	Flexible Jumpers Connecting Stripline Outer Conductor Segments	EE	Each	146		50.00	7,300					0		0		Defer	
1.1.9.4-10	Reset Power Supply	EE	Each	1		10,000.00	10,000					0		0		Defer	
1.1.9.4-11	Poly Beads to Fill Penetration Between PS Room and Target Hall	EE	Gaylord	3		1,000.00	3,000					0		0			
1.1.9.4-12	Controls Modules for HHW PS, Reset PS, and Timing	EE	Each	3		1,000.00	3,000					0		0		Defer	
1.1.9.4-13	Copper Foil for Grounding Interior of Decay Pipe at Feedthru Locations. Minimum 1/16 Inch Thick.	EE	Foot	1,533		1.00	1,533					0		0			
1.1.9.4-14	Current Transformers. One per Hadronic Hose Section.	EE	Each	72		100.00	7,200					0		0		Defer	
1.1.9.4-15	18 AWG Twisted Pair Wire, Foil Shield with Drain Wire. Alpha 2241C.	CP	Foot	90,000		0.26	23,224					0		0		Defer	
1.1.9.4-16	Fabricated Flexible Jumpers to Connect Transformer to Box Beam Stripline and Ground End of HH Wire Segment. Three Required at Each Box Beam.	EE	Each	219		6.00	1,314					0		0		Defer	
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
			TOTAL MATERIALS & SERVICES				282,071	TOTAL LABOR						0	0	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											282,071		277,538	0

TECHNICAL DESCRIPTION:

A stripline will connect the power supply to all transformers in series. Approximate total length is 725 meters or 2400 feet. The stripline is composed of a sandwich of 3 aluminum conductors separated by Lexan dielectric. Conductors are 1 foot wide and 0.125 inch thich. Except for connection between the power supply and the upstream end of the decay pipe, the stripline is provided in pre-assembled 30 foot lengths.

Grounding requirements relative to decay pipe or transformer secondaries are presently indeterminate.

Operation of transformers and stripline in a damp environment has not yet been fully addressed.

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

Estimating an additional 50 meters between Power Supply Support Enclosure and beginning of Decay Pipe.

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Figure 24: WBS element 1.1.9.4 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.5
COMPONENT or WBS DESCRIPTION: Electrical Service

NAME: Ducar
PHONE & MAIL STOP:
ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.5-1	Combination Starter for 480 VAC 10 HP Pump. Decay Pipe Cooling System. SquareD Class 8539SDG42 NEMA 1 Encl with Heater.	VQ	Each	2		1,768.00	3,536					0		0			
1.1.9.5-2	Isolating 30A 480 VAC Safety Switch for 10 HP Pump. Decay Pipe Cooling System. SquqareD HU361 30A Non-Fused NEMA 1 Encl.	VQ	Each	2		99.20	198					0		0			
1.1.9.5-3	Install Electrical Service for Decay Pipe Cooling Pumps. ~2400 Foot Run.	EE					0		2	ET	24	48	60.00	2,880	720		
1.1.9.5-4	Install Hadronic Hose PS Stripline between PS Room and Upstream End of Decay Pipe. Path is Through New Penetration and ~175 Feet in Total Length.	EE					0		3	ET	20	60	60.00	3,600	900	Defer	
1.1.9.5-5	Install HH Wire Segment Transformers. 72 Places. 2 per Hour.	EE					0		2	ET	36	72	60.00	4,320	1,080	Defer	
1.1.9.5-6	Install HHPS Stripline Segments between Transformers. 71 Segments and 3 Hour Install Time per Segment.	EE					0		3	ET	213	639	60.00	38,340	9,585	Defer	
1.1.9.5-7	Connect Transformers to Stripline and HH Wire Segments. 1 Hour per Transformer.	EE					0	PS Techs	2	TB	73	146	35.00	5,110	1,278	Defer	
1.1.9.5-8	Circuit Breakers for Hadronic Hose and Reset Power Supplies	EE	Each	2		500.00	1,000					0		0		Defer	
1.1.9.5-9	Install 120VAC Electrical Service Along Decay Pipe. Outlets at Each Box Beam Penetration.	EE					0		2	ET	40	80	60.00	4,800	1,200	Defer	
1.1.9.5-10	Fluorescent Fixture. 4 Foot Long, 2 Bulb, Magnetic Ballast, Enclosed.	A00	Each	73		95.00	6,935					0		0		Defer	
1.1.9.5-11	Install Fluorescent Fixtures at Each Transformer / Box Beam Penetration Location.	EE					0		2	ET	60	120	60.00	7,200	1,800	Defer	
1.1.9.5-12	Connect HH and Reset Power Supplies to Electrical Service	EE					0		2	ET	8	16	60.00	960	240	Defer	
1.1.9.5-13	3/4" Rigid Conduit, Wire, Couplings, Receptacles, Boxes for Lights and 120VAC Electrical Service.	EE	Foot	4,800		1.04	4,992					0		0		Defer	
1.1.9.5-14	3/4" Rigid Conduit, Wire, Couplings, Boxes for Decay Pipe Cooling Pumps.	GAQ	Foot	2,600		1.04	2,704					0		0			
1.1.9.5-15	6 Inch Cable Tray for Segment Current Monitor Wiring. Hangers and Hardware Included.	GAQ	Foot	2,400		8.37	20,088					0		0		Defer	
1.1.9.5-16	Install 6 Inch Cable Tray for Segment Current Monitor Wiring. Install at Rate of Ten 12" Sections per Shift.	EE					0		2	ET	160	320	60.00	19,200	4,800	Defer	
1.1.9.5-17	Pull Twisted Pair Monitor Cable Between 72x Current Transformers and Power Supply Room.	EE					0		2	ET	18	36	60.00	2,160	540	Defer	
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
			TOTAL MATERIALS & SERVICES				39,453	TOTAL LABOR						88,570	22,143	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											128,023		140,128	0

TECHNICAL DESCRIPTION:

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

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Figure 25: WBS element 1.1.9.5 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.6

COMPONENT or WBS DESCRIPTION: Research and Development

NAME: May, Pushka, and Ducar

PHONE & MAIL STOP:

ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.6-1	Miscellaneous Materials Cost for Research & Development Activities.	EE	Lot	1		5,000.00	5,000					0		0			
1.1.9.6-2	Develop an Appropriate Hadronic Hose Wire Straightening Technique. Strategies Currently Include Stretching, Twisting, and Running the Wire Through a Series of Rollers. Apply to Various Wire Candidates. Quantify Affect on Creep and Electrical Conductivity.	EE	Lot	1		10,000.00	10,000		1	EN or PH	40	40	60.00	2,400			12,400
1.1.9.6-3	"	EE					0		1	TB	100	100	35.00	3,500			3,500
1.1.9.6-4	Perform Mechanical Vibration Testing of Hadronic Hose Wire Metal and Alloy Candidates. Primary Concern is Strain Hardening. Quantify Affect on Conductivity.	EE	Lot	1		2,500.00	2,500		1	EN or PH	40	40	60.00	2,400			4,900
1.1.9.6-5	"	EE					0		1	TB	60	60	35.00	2,100			2,100
1.1.9.6-6	Perform Long Term Creep Tests of Various Hadronic Hose Wire Metal and Alloy Candidates. Testing Should Be Over Defined Ranges of Temperature and Tension. Expecting a 3 to 6 Month Testing Duration.	EE	Lot	1		10,000.00	10,000		1	EN or PH	60	60	60.00	3,600			13,600
1.1.9.6-7	"	EE					0	Mechanical	1	TB	160	160	35.00	5,600			5,600
1.1.9.6-8	Prototype 40 Foot Open Ended Section Decay Pipe. Completely Fabricated and Placed on 3 Degree Slope. Capable of Operating Full 30 Foot Hadronic Hose Segment and Two Abbreviated Adjacent Sections. Also Outfit With Strength Ribs and Cu Pipe.	EE	Lot	1		50,000.00	50,000	Mechanical	1	EN	120	120	60.00	7,200			
1.1.9.6-9	Welder Services for Box Beam, Feedthrus, Spider and Tensioning Bracket Installation. Work to Include Layout.	EE					0		1	WC	80	80	60.00	4,800			
1.1.9.6-10	Outfitting of Prototype Decay Pipe.	EE	Lot	1		2,500.00	2,500	Mech Tech	2	TB	80	160	35.00	5,600			2,500
1.1.9.6-11	Perform Electrical Pulse Testing of Hadronic Hose Wire. To Be Performed in Decay Pipe Prototype With Design 1000A Pulse Applied. Interested in Induced Motion of Wire Segment and Motion Induced by Currents in Adjacent Segments.	EE	Lot	1		10,000.00	10,000	Electrical	2	EN	160	320	60.00	19,200			
1.1.9.6-12	"	EE					0	Elec Tech	2	TB	160	320	35.00	11,200			
1.1.9.6-13	Investigate Potential of Electrical Discharge of Hadronic Hose Wire Operating at Voltage and in Vacuum in a High Radiation Environment.	EE					0		1	PH	480	480	60.00	28,800			28,800
1.1.9.6-14	"	EE					0	Electrical	1	EN	80	80	60.00	4,800			4,800
1.1.9.6-15	Determine Optimal Aluminum Wire Anodization Thickness as Related to Thermal Emissivity and Brittleness.	EE					0		1	EN or PH	120	120	60.00	7,200			7,200
1.1.9.6-16	Convert Open Ended Prototype Decay Pipe to Vacuum Vessel. Includes End Bells, Flanges, and Pump Ports.	EE	Lot	1		75,000.00	0	Mechanical	1	EN	80	80	60.00	0		Deleted from Scope	
1.1.9.6-17	Full Scale Electrical Test of Hadronic Hose Segment in Vacuum.	EE					0	Elec/Mec	2	EN	40	80	60.00	0		Deleted from Scope	
1.1.9.6-18	"	EE					0	Elec/Mec	2	TB	40	80	35.00	0		Deleted from Scope	
1.1.9.6-19	Pipe Crawler Concept Research and Development.						0	Mechanical	1	EN	120	120	60.00	7,200			7,200
1.1.9.6-20	Design Drafter Services for R&D Efforts						0		1	DS	200	200	45.00	9,000			
							0					0		0			
							0					0		0			
							0					0		0			
			TOTAL MATERIALS & SERVICES				90,000	TOTAL LABOR						124,600	0	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											214,600			92,600

TECHNICAL DESCRIPTION:

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

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Figure 26: WBS element 1.1.9.6 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.7
COMPONENT or WBS DESCRIPTION: Installation

NAME: May and Ducar
PHONE & MAIL STOP:
ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.7-1	Weld 1,944 Spider Supports to Inner Decay Pipe Wall. 3 Supports per Spider. 9 Spiders per Segment. 72 Segments. 7 Hr per Segment.	EE					0	Welder	2	WC	504	1,008	60.00	60,480	15,120		
1.1.9.7-2	Weld 288 Tensioning Supports to Inner Decay Pipe Wall. 4 Supports per Segment. 72 Segments. 1 Hr per Segment.	EE					0	Welder	2	WC	72	144	60.00	8,640	2,160		
1.1.9.7-3	Install Spider Support Assemblies in Decay Pipe. 27 per Segment. 3.5 Hours per Segment.	EE					0	Mech Techs	2	TB or TC	252	504	35.00	17,640	4,410		
1.1.9.7-4	Install Tensioning Support Assemblies. 4 per Segment. 30 Minutes per Segment.	EE					0	Mech Techs	2	TB or TC	36	72	35.00	2,520	630		
1.1.9.7-5	Drill Out Pilot Holes and Face Off Inside of Decay Pipe Wall at Feedthru Locations. 144 Places. 4 Holes per Hour.	EE					0	Mech Techs	2	TB or TC	36	72	35.00	2,520	630		
1.1.9.7-6	Weld HH Wire Feedthrus to Inside of Decay Pipe Wall. 144 Places. 4 Welds per Hour. 10% of Time Added for Reworks After Leak Checks.	EE					0	Welder	2	WC	40	79	60.00	4,752	1,188		
1.1.9.7-7	Install HH Wire Segment. Work Includes Attachment to Spider and Tensioning Support Assemblies, and Installation/Soldering of Feedthru Connection. 72 Segments. 8 Hours per Segment.	EE					0	Mech Techs	2	TB or TC	576	1,152	35.00	40,320	10,080		
1.1.9.7-8	Final Assembly of Box Beam Stripline. Includes Remote Attachment of Decay Pipe Grounding Connection, Alignment of Feedthru Conductors in Step With 1.1.9.7-6, Insertion of Dielectric, and Strapping of Stripline.	EE					0	Elec Techs	2	TB	73	146	35.00	5,110	1,278		
1.1.9.7-9	Load Box Beam With Foam Inserts and Poly Beads. 1 Hour per Box Beam.	EE					0	Mech Techs	2	TB or TC	73	146	35.00	5,110	1,278		
1.1.9.7-10	Buff, Clean, and Wipe Down Interior Wall of Decay Pipe at Each Feedthru Location Prior to Installation of Grounding Copper Foil. 2 Hours per Location.	EE					0	Welder	2	WC	146	292	60.00	17,520	4,380		
1.1.9.7-11	Silfloss Interior Grounding Copper Foil at Each Feedthru Location. 2 Locations per Hour.	EE					0	Welder	2	WC	37	73	60.00	4,380	1,095		
1.1.9.7-12	Terminate Current Monitoring Cable. 144 Terminations Total.	EE					0	Elec Techs	2	TB	12	24	35.00	840	210	Defer	
1.1.9.7-13	Electric Crawler Cart for Transportation of Personnel (2 Minimum) and Equipment in Decay Pipe.	EE	Each	2		15,000.00	30,000					0		0			30,000
1.1.9.7-14	Temporary Lighting Fixtures and Electrical Service for Inside Decay Pipe During Installation Activities.	EE	Lot	1		3,000.00	3,000					0		0			
1.1.9.7-15	Dye Penetrant Leak Check of Ceramic Feedthrus. Staged Work at 73 Places.	EE					0	Mech Techs	2	TB	73	146	35.00	5,110	1,278		
							0					0		0			
							0					0		0			
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			TOTAL MATERIALS & SERVICES				33,000	TOTAL LABOR						174,942	43,736	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											207,942		1,050	30,000

TECHNICAL DESCRIPTION:

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

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Figure 27: WBS element 1.1.9.7 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.8

COMPONENT or WBS DESCRIPTION: Survey

NAME: Hylen, May and Ducar

PHONE & MAIL STOP:

ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.8-1	Spot 144 Holes for Electrical Feedthrus on Interior of Decay Pipe. 8 Inch Spacing and 30 Foot Intervals Along Entire Length of Decay Pipe.						0		3	AC or AF	40	120	40.00	4,800	1,200		6,000
1.1.9.8-2	Spot Locations for Interior Spider Supports. 33 per Segment and 72 Segments. These are Non-Critical Locations and Can Be Easily Spotted by Techs with a Tape Measure Using Feedthru Holes as Reference..						0		2	TB or TC	10	20	35.00	700	175		
1.1.9.8-3	Align HH Wire. 15 Alignment Crew Shifts from Proposal Plus 5 Shifts to Accommodate Increased Number of Spider Supports. Desired +/- 2mm Accuracy.						0		3	AC or AF	160	480	40.00	19,200	4,800		24,000
							0					0		0			
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			TOTAL MATERIALS & SERVICES				0	TOTAL LABOR						24,700	6,175	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											24,700			30,000

TECHNICAL DESCRIPTION:

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

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Figure 28: WBS element 1.1.9.8 cost estimate for hadronic hose.

NuMI HADRONIC HOSE

WORK PACKAGE COST ESTIMATE DETAIL SHEET

WORK PACKAGE WBS CODE (LEVEL 4): 1.1.9.9
COMPONENT or WBS DESCRIPTION: EDI&A

NAME: May, Puska, Pfeffer and Ducar
PHONE & MAIL STOP:
ESTIMATE DATE: 7-Apr-00 11:45 AM

			MATERIALS & CONTRACTED SERVICES					LABOR									
ITEM WBS (LEVEL 5)	DESCRIPTION	COST BASIS	UNIT MEASURE	NUMBER OF UNITS	Ayy $ PER UNIT	FY00 $ PER UNIT	TOTAL M&CS $	RESOURCE NAME	NMBR OF PEOPLE	LABOR TYPE	HOURS PER PERSON	TOTAL HOURS	$ COST PER HOUR	TOTAL LABOR $	DOWN HOLE PENALTY	COMMENT	PROVIDED BY OTHERS
1.1.9.9-1	Design Fixture for Spotting and Pre-Tack Holding of Spider Supports	EE					0	Mechanical	1	EN	20	20	60.00	1,200			
1.1.9.9-2	Design Fixture for Spotting and Pre-Tack Holding of Tensioning Spring Supports. This Fixture Will Attach to the Spider Fixture.	EE					0	Mechanical	1	EN	15	15	60.00	900			
1.1.9.9-3	Design HH Wire Bending Fixture	EE					0	Mechanical	1	EN	10	10	60.00	600			
1.1.9.9-4	Design Spider Support Invar Wire Bending Fixture	EE					0	Mechanical	1	EN	4	4	60.00	240			
1.1.9.9-5	Design HH Wire Strongback. 30 Feet Long with 3 Foot Arms.	EE					0	Mechanical	1	EN	16	16	60.00	960			
1.1.9.9-6	Drafting Support for WBS 1.1.9.10-1 to -5	EE					0	Mechanical	1	DR	80	80	40.00	3,200			
1.1.9.9-7	Design Insulating Spider Support Bracket	EE					0	Mechanical	1	EN	4	4	60.00	240			
1.1.9.9-8	Design Insulating Tensioning Spring Bracket	EE					0	Mechanical	1	EN	4	4	60.00	240			
1.1.9.9-9	Design Feedthru Assembly	EE					0	Mechanical	1	EN	20	20	60.00	1,200			
1.1.9.9-10	Drafting Support for WBS 1.1.9.10-7 to 9	EE					0	Mechanical	1	DR	16	16	40.00	640			
1.1.9.9-11	Design Decay Pipe Cooling System	EE					0	Mechanical	1	EN	320	320	60.00	19,200			
1.1.9.9-12	Drafting Support for Decay Pipe Cooling System	EE					0	Mechanical	1	DR	480	480	40.00	19,200			
1.1.9.9-13	Design Fixture to Adapt Magnetic Base Drill to Inner Decay Pipe Wall	EE					0	Mechanical	1	EN	8	8	60.00	480			
1.1.9.9-14	Design Stripline Strongback	EE					0	Mechanical	1	EN	16	16	60.00	960		Defer	
1.1.9.9-15	Design HH Wire Power Supply, Transformers, and Reset PS.	EE					0	Electrical	1	EN	400	400	60.00	24,000		Defer	
1.1.9.9-16	Design HH Wire Power Supply Stripline.	EE					0	Electrical & Mechanical	2	EN	100	200	60.00	12,000		Defer	
1.1.9.9-17	Drafting Support for WBS 1.1.9.10-14 to 16	EE					0	Electrical & Mechanical	2	DR	100	200	40.00	8,000		Defer	
1.1.9.9-18	Hadronic Hose Project Ovesight. 6 Months at 40% Full-Time	EE					0	Roofer	1	EN	416	416	60.00	24,960			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
							0					0		0			
			TOTAL MATERIALS & SERVICES				0	TOTAL LABOR						118,220	0	TOTAL DEFERRED	TOTAL BY OTHERS
			TOTAL MATERIALS & CONTRACTED SERVICES and LABOR COSTS											118,220		44,960	0

TECHNICAL DESCRIPTION:

ESTIMATE ASSUMPTIONS:

Decay Pipe Length = 675 Meters or 2,215 Feet. Decay Pipe Inside Diameter = 2 Meters or 6 Feet 7 Inches.

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Figure 29: WBS element 1.1.9.9 cost estimate for hadronic hose.

13 Further R&D

We divide the set of materials tests and prototyping tasks into two groups: those which are essential, and those which we would like to do but could be dropped if resource constraints are too tight. The essential tasks are:

- Do long term creep tests of several wire material candidates. This is already underway, with 16 samples of different materials being held at varying tempertures and tensions. Because creep goes through an initial higher rate phase, and then a slower long term phase, good measurements require probably three to six months. Work to try to locate even better alloys for our purpose is also highly desirable.

- Develop a wire straightening technique. The wire is delivered wound on a spool. We need to make 40 foot sections, of which the central 30 foot section must be straight. There are several techniques we know of for doing this: stretching a warm wire, twisting the wire, or running the wire through a set of rollers. We have not tested any of these yet.

- Do a long term wire vibration/pulse test. Our test power supply currently has a 3 ms half-sine-wave baseline. We need to modify the supply to give the 0.3 ms pulse that we plan to use in the actual hose, and do a long term pulse test on a wire. In addition, a fixture is available to mechanically vibrate a wire, which would allow vibration testing of more samples more quickly.

- Construct a full scale prototype of one complete hose section plus part of an adjacent section. We intend to obtain about 40 feet of 2 m diameter steel pipe and mount it on a 3 degree slope to simulate the decay pipe. We will then practice installation and survey operations. This would be a prototype test for all hose hardware except the power supply and stripline. It also allows a measurement of hose induction, to check against design calculations, before construction of the final power supply.

Lower priority tests are:

- Check on electrical discharge in a high radiation environment. This can be accomplished by taking a small cell (perhaps part of the current hadronic hose test stand) to a high radiation area (e.g. in the Booster beam in front of the Booster absorber, in Main Injector beam in front of the Main Injector abosorber), and operating it with voltage and vacuum.

- Optimize the aluminum wire anodization thickness. We have tried three coatings so far for the aluminum wire: i) iriditing, which ended up with too low an emissivity, ii) 3 mil thick black hard coat class III anodizing, which had good emissivity (approximately 0.7), but which was very brittle, and iii) 10 micron (0.4 mil) electrolytic anodizing, which was not brittle, but has a somewhat lower emissivity of 0.5. The 0.5 emissivity is acceptable, but boosting the thickness to e.g. 20 micron might improve the emissivity to 0.7 or 0.8, which would help the wire to run cooler, and thus increase its lifetime.

- Check on full scale model in vacuum. There are two places on the FNAL site where 2 m diameter decay pipes already exist: the KTeV and neutrino lines. It would be possible to put a wire in either one, and check cooling and electrical breakdown without having to scale from the smaller test cell. Another possibility is, since NuMI in any case must fabricate decay pipe end flanges and windows, to accelerate their construction and use them in a full scale test cell that can be evacuated.

A Appendix: Segment Failure

Residual radiation levels in the decay pipe will be high enough that human entry to repair failed hose segments is very problematic. The strategy taken is to make hose components very robust, and to make the hose in a sufficient number of segments that failure of a reasonable fraction of them will not compromise hose operation. In the proposal, a failure of 10% of the segments was shown to have minimal impact.

Access to the decay pipe passage-way is possible, to disconnect failed sections, repair failed transformers, or fix problems with the stripline, although a couple day radiation cooldown period may be required after sustained running.

Under currently envisioned conditions, the Aluminum wire is operating at modest temperature and stress, of order 100°C and 290 PSI. The wire tension is only 2 lbs, and the force on the spider wires is only ounces. The mechanical impulse due to the electrical forces and rapid joule heating of the wire is also much reduced by the change to single turn extraction and the resulting shorter pulse length. The two failure modes of most concern are slow creep of the aluminum wire (which we believe further testing will show well under control), and primary beam mis-steering where a beam pulse manages to miss the target but still edge through the horn-protection baffle. Mis-steered beam would be pulled into the wire by the hose focusing. Although the resulting beam heating would not be enough to melt the wire, this scenerio has not been studied to see if dynamic stress or other effects might damage the wire.

As a precaution, the constant tension spring extension should be set to bottom out before a broken segment would run into the next segment.

B Appendix: Radiation

B.1 Radiation Dose

The first section of pulsed wire will receive 1.7×10^{11} rads/year at design luminosity of 3.7×10^{20} protons on target per year. Only anodized aluminum and invar hose components are used here.

The maximum radiation dose to the components at the decay pipe walls is 10^9 Rads/year, occuring about 50 m from the upstream end of the decay pipe. The rate at the downstream end is an order of magnitude less.

The transformers and striplines in the passage-way along the decay pipe will receive of order $0.2{\times}10^6$ rad/year.

The power supply is in a well shielded room, with unlimited human occupancy, and the radiation dose is expected to be quite small.

B.2 Residual Rates

The residual radiation rates in the decay pipe are fairly high, a few R/hr. Given the constricted nature of the interier of the decay pipe, a useful access would take an extended period of time. With this combination, no human access is forseen.

The decay pipe passage-way is interlocked during beam operation. After an extended period of design-luminosity running, the passage-way is expected to have a residual rate of 800 mR/hr with no cooldown, and 8 mR/hr after 4 days [5]. Thus a few day wait is expected before a repair would be attempted on the hose stripline or transformer in the case of a failure.

B.3 Groundwater Protection

The star densities in the rock surrounding the decay pipe have been estimated using a MARS simulation of the NuMI beamline. Various configurations of the beam line have been simulated including the hadronic hose and beam plug options. Estimates of the star densities in the rock assume the use of 140-weight concrete and the TBM (Tunnel Boring Machine) shielding configuration. Results are summarized in Table 5. Reglatory limits on ground water concentrations of

		10^{-11} Star/cm^3 (Fraction of Limit)	
		Up Stream	Down Stream
	Regulatory Limit	1.50 (1.00)	2.10 (1.00)
1	PH2L	1.25 (0.83)	1.10 (0.52)
2	PH2L HH	1.31 (0.87)	1.60 (0.76)
3	PH2L BP	0.98 (0.65)	0.30 (0.14)
4	PH2L BP/HH	1.11 (0.74)	0.39 (0.19)
5	PH2M	1.07 (0.71)	0.95 (0.45)
6	PH2M HH	1.12 (0.75)	1.10 (0.52)

Table 5: Estimated star densities in the up stream and down stream rock regions surrounding the decay pipe. Results are shown for several beam configurations: (1) low-energy beam (PH2L), (2) low-energy beam with hadronic hose (HH) option, (3) low-energy beam with beam plug (BP) option, (4) low-energy beam with beam plug and hadronic hose options, (5) medium-energy beam (PH2M), (6) medium-energy beam with hadronic hose option.

^{3}H and ^{22}Na place an upper limit on the star densities in these regions of 1.50×10^{-11}/cm^3 and 2.10×10^{-11}/cm^3. Addition of the hadronic hose increases the star densities by roughly 5-15%, however all estimates are still within regulatory limits. The star density closest to regulatory limits (low energy beam with hadronic hose) is 13% below the regulatory limit. Simulations of the high energy beam with hadronic hose option have not been made.

B.4 Cooling Water Activation

Radiation penetrating through the decay pipe wall will produce residual radioactivity in the closed-loop water cooling it. The radionuclide of principal concern is tritium, due to its relatively long half-life (12.3 years) and the fact that it is not removed from the closed-loop water in the de-ionization process. The following is an estimate of the tritium build-up in the hadronic hose cooling water.

A MARS Monte Carlo calculation yields an average hadronic flux in the decay pipe steel of 2.73×10^{-6}hadrons cm^{-2}proton-on-target^{-1} [6]. At the NuMI design goal of 4×10^{13}protons per pulse, with one pulse every 1.9 s, the average hadronic flux in the decay pipe is then $\Phi = 5.75 \times 10^6$hadrons cm^{-2}s^{-1} .

For the purposes of this estimate, the hadronic flux through the water is assumed to be the same as that in the steel. The volume of water exposed to irradiation at any time is $1.2 \times 10^6 \text{cm}^3$. The total path length of hadrons in water per second is then $\Phi V = \left(5.75 \times 10^6 \text{cm}^{-2}\text{s}^{-1}\right)\left(1.2 \times 10^6 \text{cm}^3\right) = 6.90 \times 10^{13}$ h cm s^{-1}.

The production rate of tritium in water for 10^{12}hadrons passing through 1 cm of water in 1 s is given by Sullivan [7] as R =1.8 Bq.

The activity of tritium in the water at time t is then given by $A(t) = \Phi V R t \left(1 - e^{-\lambda t}\right)$, where $\lambda = 1.8 \times 10^{-9} \text{s}^{-1}$is the decay constant of tritium. Setting $t = 3.1 \times 10^7$s (one year), $A(1yr) = 2.1 \times 10^8$ Bq.

The total volume of water in the system is four times that which is in the cooling pipes at any given time, so the concentration of tritium activity in the closed loop system is $C(t) = \frac{A(t)}{4V}$, and $C(1 \text{ yr}) = \frac{5.6 \times 10^9 \text{pCi}}{4.8 \times 10^6 \text{cm}^3} \approx 1200$ pCi cm^{-3}, where the conversion of 1Bq = 27 pCi has been applied. The Derived Concentration Guide (DCG) limit as given by the Department of Energy [8] is 2000 pCi cm^{-3}. Hence, the tritium levels in the cooling water should remain below the DCG level after one year. This estimate is conservative in that it ignores the duty factor of the Main Injector.

C Appendix: Residual gas ionization

The charged particles passing through the NuMI decay pipe ionize the residual gas, which drift under the influence of the hadronic hose wire voltage. Since the wire will be anodized, and thus have an insulating layer, there will be a surface charge build up and the ionization current will then stop flowing. Also, the strong magnetic field near the wire will curl up ion trajectories.

It is interesting however to get a first order estimate of the size of the drift current. A GEANT Monte Carlo run gives about 1.4 charged particles per proton on target at the beginning of the decay pipe, and about 0.5 charged particles per proton at the end of the decay pipe. The design proton intensity is 4×10^{13} per 8 μsec spill. ICRU Report 31 "Average Energy Required to Produce An Ion Pair" (International Commission on Radiation Units and Measurements, 1 May, 1979) states that the mean energy taken to produce an ion pair in air is 34 eV. dE/dx(min) in air is 1.82 MeV cm^2/g and the density at atmospheric pressure is 1.29 g/l. The vacuum in the NuMI decay pipe could be selected to be anywhere from about 10^{-2} torr (reasonably easy to achieve with fairly inexpensive vacuum system) to 10 torr (where reduction of the neutrino rate would start to be measurable).

If we assumed the drift time was small compared to the 8 μsec spill, then for a 10^{-2} torr to 10 torr vacuum the current from ions would be estimated to be 1.1 Amp to 1.1 kA per 11 m long hadronic hose section. For the higher pressure cases, further calculations using realistic mobilities and with consideration of space charge effects and charging of the anodization layer are needed. For the 0.1 torr baseline design, the effect should be negligible.

References

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[7] A.H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Acclerators, Nuclear Technology Publishing, Ashford, Kent, England, 1992.

[8] DOE Order 5400.5 (1990)